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THESIS

A METHODICAL DEVELOPMENT OF MEASURES OF EFFECTIVENESS FOR A CONDITION-BASED MAINTENANCE MANAGEMENT SYSTEM

by

Hector A. Ojeda

June 2014

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13. ABSTRACT (maximum 200 words)

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A set of eight MOEs is developed using the nine-step method, a systems engineering (SE) focused approach that uses an integrative framework of objective values and subjective criteria to guide the development of MOEs.

A maintenance organization may use the developed set of eight CMMS MOEs to determine how well the CMMS is being employed within the organization and how well it supports a CBM+ approach. The MOE set provides basic indicators to determine the effectiveness of the CMMS functions and of the system as an object. The developed MOEs also address the initial set of stakeholder requirements and needs.

Maintenance organizations can use the development processes established by the nine-step methodology to develop valid, significant, and useful MOEs for system's fitness-for-purpose evaluation and determination. The nine-step method is practicable within a typical surface maintenance organization.

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A METHODICAL DEVELOPMENT OF MEASURES OF EFFECTIVENESS FOR A CONDITION-BASED MAINTENANCE MANAGEMENT SYSTEM

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LIST OF ACRONYMS AND ABBREVIATIONS

CBM	condition-based maintenance
CBM+	condition-based maintenance plus
CM	corrective maintenance
CMMS	computerized maintenance management system
CNO	Chief of Naval Operations
COI	critical operational issue
COTS	Commercial Off-The-Shelf
DAG	Defense Acquisition Guidebook
DOD	Department of Defense
DON	Department of the Navy
EAM	enterprise asset management
EMMI	energy, matter, material wealth, and information
INCOSE	International Council on Systems Engineering
IT	information technology
LCS	Littoral Combat Ship
MOE	measure of effectiveness
MOP	measure of performance
NAVSEA	Naval Sea Systems Command
OT&E	operational testing and evaluation
PM	preventive maintenance
RCM	reliability-centered maintenance
SE	systems engineering
SF	ship's force
SMMO	Ship Maintenance and Materiel Officer

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EXECUTIVE SUMMARY

In May 2013, the Naval Sea Systems Command (NAVSEA) established policy implementing condition-based maintenance plus (CBM+) as the maintenance approach of choice to reduce and control ship's lifecycle costs (Naval Sea Systems Command 2013, 1). CBM+ implementation represents a fundamental shift from the traditional Navy maintenance management methods used to control preventive maintenance (PM) and corrective maintenance (CM). The Navy's legacy fleet has been built around a PM and CM system with a foundation on reliability-centered maintenance (RCM) analysis. Platforms that support a CBM+ strategy require a significant quantity of sensors and meters to build an accurate maintenance history, as well as a computerized maintenance management system (CMMS) for real time data collection and display. A successful CBM+ program relies on the collection and management of accurate real-time system component data that enables decision makers to increase system availability by scheduling maintenance only when it is required. The correct implementation of CBM+ should result in reduced total ownership costs and improved system availability (Department of Defense 2008, 1-3).

The Littoral Combat Ship (LCS) is the only class of currently deployed ships implementing the CBM+ maintenance approach early in their lifecycle. The LCS program's operational concept requires contractors to manage an increasing portion of the ship's maintenance using Commercial Off-The-Shelf (COTS) CMMS programs. The LCS' non-traditional reduced manning concept requires LCS maintenance managers to develop strategies using RCM and untried condition-based maintenance (CBM) approaches (Commander, U.S. Fleet Forces Command 2013). LCS program contractors use Maximo, an IBM developed enterprise asset management (EAM) program, to manage maintenance.

At their core, CMMS programs are information databases with customizable interfaces to aid decision makers in determining the best path to manage maintenance. Contractor-driven maintenance management using a COTS CMMS program is a sharp departure from the traditional surface Navy maintenance management process. Successful CMMS implementation is influential a CBM+ program's success.

CMMS programs are instrumental in the effective implementation of a CBM+ strategy, yet there is a lack of consistent methodology to measure CMMS implementation effectiveness as it pertains to CBM+. The problem that results from the lack of a well-defined and methodically derived set of measures of effectiveness (MOE) is that CBM+ maintainers cannot properly determine or monitor how well the selected CMMS program accomplishes its intended operational objectives. MOEs are important during system selection and become crucial during system effectiveness monitoring and change implementation throughout the system's lifecycle because when correctly selected they indicate how well a system is fit for its intended purpose. Currently there is no method that provides a set of objective values and subjective criteria for MOE development.

The objective of this thesis is to utilize a consistent systems engineering (SE) approach to develop an initial set of MOEs that help define the successful operational use of a CMMS program in the implementation of a CBM+ strategy. MOEs will be developed using a framework that provides a consistent methodical approach to determine the effectiveness of a selected CMMS.

The results of this thesis will provide an initial set of MOEs for the usage of a CMMS in support of ship maintenance. The MOEs will be developed using a consistent analytical framework method that allows for iterations. The CMMS is a singular component of a more complex system required for the successful establishment of a CBM+ strategy. Although it is but a component in a management system, it often contains the information dashboard used by decision makers when controlling maintenance. A well-developed set of CMMS MOEs will benefit the maintenance community in determining how well the employed system is meeting the organization's needs.

MOEs were characterized using a modified application of Langford's nine-step method that allows the MOE development concept to become repeatable, and able to be validated with operational and managerial needs (G. Langford, Determinants of Deterrence Effectiveness 2014, 7-12). This research only used the first seven steps of the nine-step method. The last two steps are better used during MOE reevaluation. The seven steps used in this study and their application to CMMS MOE development are described below (G. Langford, Determinants of Deterrence Effectiveness 2014, 7-12):

- Define terminology: Defined CMMS, CBM+, and other maintenance management working terms to determine the research scope.
- Delineate boundaries and functions: Performed a functional analysis of the key measurable CMMS and management functions.
- Perform lifecycle analysis: Defined the life cycle of the key measurable CMMS and management functions.
- Define requirements: Derived stakeholder requirement by analyzing solicited stakeholder needs.
- Postulate solution set: Developed a set of solutions to satisfy the problem domain issues.
- Determine theoretical foundations: Applied management maintenance and logistics theory to the problem issue.
- Formalize framework: Mapped subjective elements to objective elements using the integrative framework.

The following is a summary of the CMMS MOEs were developed using the integrative framework.

MOE	Description
MOE-e: CMMS experience	Cognition-Object: Provides insight into the effectiveness of system usage as it relates to recording, updating, coordination, and communication of maintenance data.
MOE-r: CMMS Response	Cognition-Object: Provides insight into the effectiveness of the management and reporting of maintenance data and the system's interface with objects.
MOE-g: CMMS Functionality Prediction	Cognition-Function: Provides insight into the effectiveness of the predicted functional results arising from interactions between the systems and data reporting objects.
MOE-c: CMMS Functionality Expectation	Cognition-Function: Identifies user satisfaction based on system expectations.
MOE-s: CMMS Selection Validity	Procedure-Object: Identifies the high level stakeholder's satisfaction based on programmatic goals.
MOE-x: CMMS Operational Context Validity	Procedure-Object: Identifies the CMMS' ability to interact with external objects.
MOE-u: CMMS Functional Resource Utilization Validity	Procedure-Function: Provides insight into the efficiency of the CMMS' functions to support resource management.
MOE-b: CMMS Functional Boundary Conditions	Procedure-Function: Provides a metric of the CMMS' function's ability to interact with external objects.

Figure 1 CMMS MOE Summary

A maintenance organization may use the developed set of eight CMMS MOEs to determine how well the CMMS is being employed within the organization and how well it supports a CBM+ approach. The MOE set provides basic indicators to determine the effectiveness of the CMMS function's and of the system as an object. The developed MOEs also address the initial set of stakeholder requirements and needs.

Maintenance organizations can use the development processes established by the nine-step methodology to develop valid, significant, and useful MOEs for system's fitness-for-purpose evaluation and determination. The nine-step method is practicable within a typical surface maintenance organization. Developing and iterating MOEs will only require staff with an understanding of the overarching programmatic goals and knowledge of the evaluated systems due to the method's simple and direct approach. The process could also be extended to MOE development in other areas.

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I. INTRODUCTION

A. A FUNDAMENTAL SHIFT IN MAINTENANCE MANAGEMENT

In May 2013, the Naval Sea Systems Command (NAVSEA) established policy implementing condition-based maintenance plus (CBM+) as the maintenance approach of choice to reduce and control ship's lifecycle costs (Naval Sea Systems Command 2013, 1). CBM+ implementation represents a fundamental shift from the traditional Navy maintenance management methods used to control preventive maintenance (PM) and corrective maintenance (CM). The Navy's legacy fleet has been built around a PM and CM system with a foundation on reliability-centered maintenance (RCM) analysis. Platforms that support a CBM+ strategy require a significant quantity of sensors and meters to build an accurate maintenance history, as well as a computerized maintenance management system (CMMS) for real time data collection and display. A successful CBM+ program relies on the collection and management of accurate real-time system component data that enables decision makers to increase system availability by scheduling maintenance only when it is required. The correct implementation of CBM+ should result in reduced total ownership costs and improved system availability (Department of Defense 2008, 1-3).

The Littoral Combat Ship (LCS) is the only class of currently deployed ships implementing the CBM+ maintenance approach early in their lifecycle. The LCS program's operational concept requires contractors to manage an increasing portion of the ship's maintenance using Commercial Off-The-Shelf (COTS) CMMS programs. The LCS' non-traditional reduced manning concept requires LCS maintenance managers to develop strategies using RCM and untried condition-based maintenance (CBM) approaches (Commander, U.S. Fleet Forces Command 2013). LCS program contractors use Maximo, an IBM developed enterprise asset management (EAM) program, to manage maintenance.

At their core, CMMS programs are information databases with customizable interfaces to aid decision makers in determining the best path to manage maintenance. Contractor-driven maintenance management using a COTS CMMS program is a sharp

departure from the traditional surface Navy maintenance management process. Successful CMMS implementation is influential a CBM+ program's success.

B. PROBLEM STATEMENT

CMMS programs are instrumental in the effective implementation of a CBM+ strategy, yet there is a lack of consistent methodology to measure CMMS implementation effectiveness as it pertains to CBM+. The problem that results from the lack of a well-defined and methodically derived set of measures of effectiveness (MOE) is that CBM+ maintainers cannot properly determine or monitor how well the selected CMMS program accomplishes its intended operational objectives. MOEs are important during system selection and become crucial during system effectiveness monitoring and change implementation throughout the system's lifecycle because when correctly selected they indicate how well a system is fit for its intended purpose. Currently there is no method that provides a set of objective values and subjective criteria for MOE development.

C. OBJECTIVE AND SCOPE

The objective of this thesis is to utilize a consistent systems engineering (SE) approach to develop an initial set of MOEs that help define the successful operational use of a CMMS program in the implementation of a CBM+ strategy. MOEs will be developed using a framework that provides a consistent methodical approach to determine the effectiveness of a selected CMMS.

The scope of this research includes the development of an initial set of CMMS MOEs based on user needs and requirements to measure the success of the operational use of the CMMS. Needs and requirements are derived from the LCS CONOPS, established policy requirements, and stakeholder input. This thesis uses the LCS program as a case study because they are the surface program that has implemented a CBM+ approach for the longest time. The LCS program has also implemented the CBM+ approach early in their lifecycle as opposed to other class types that have implemented traditional maintenance approaches for decades.

For the purpose of this thesis the CMMS program strictly refers to its use as a maintenance management system and not as an EAM program. Although the chosen CMMS

might have the capability to collect and analyze the required data to function as an EAM, its use in the maintenance program is limited to maintenance management. EAM functionalities require the use of a CMMS to manage funds, personnel, and a supply chain among other items.

1. Research Questions

- How can the fitness-for-purpose of a CMMS program be measured?
- How can a singular reproducible method be used to develop CBM+ maintenance management MOEs?
- How can CMMS MOEs be developed using both objective and subjective criteria?

D. SIGNIFICANCE OF THE STUDY

The results of this thesis will provide an initial set of MOEs for the usage of a CMMS in support of ship maintenance. The MOEs will be developed using a consistent analytical framework method that allows for iterations. The CMMS is a singular component of a more complex system required for the successful establishment of a CBM+ strategy. Although it is but a component in a management system, it often contains the information dashboard used by decision makers when controlling maintenance. A well-developed set of CMMS MOEs will benefit the maintenance community in determining how well the employed system is meeting the organization's needs.

E. ORGANIZATION OF STUDY

- Chapter I: Introduction
- Chapter II: Navy Ship Maintenance and CMMS Background
- Chapter III: Literature Review: Measures of Effectiveness
- Chapter IV: Methodology
- Chapter V: Measures of Effectiveness Development
- Chapter VI: Measures of Effectiveness Set Discussion

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II. NAVY SHIP MAINTENANCE AND CMMS BACKGROUND

It is useful to understand traditional maintenance strategies to fully grasp condition-based maintenance plus (CBM+) as a concept and how it benefits from the correct implementation of a computerized maintenance management system (CMMS) program. This chapter provides a brief overview of the traditional surface Navy maintenance strategies. It also provides a brief background on CMMS as a system and its selection process. Understanding the process of justifying and selecting the CMMS provides insight on how to better approach the development of measures of effectiveness (MOE).

A. MAINTENANCE OVERVIEW

The International Council on Systems Engineering (INCOSE) (1998, 136–137) defines maintenance as "those actions required to restore or maintain an item to a serviceable condition" and "the combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function.

Organizations may use several maintenance management approaches and strategies based on their maintenance needs. Traditionally all maintenance strategies seek to keep or upkeep an object in a materiel condition in which it can operate as designed.

1. Surface Navy Maintenance

Navy ship maintenance is categorized as proactive or corrective maintenance.

a. Proactive Maintenance

Navy proactive maintenance is accomplished using three approaches:

- reliability-centered maintenance (RCM)
- preventive maintenance (PM)
- CBM+

(1) Reliability-Centered Maintenance

RCM is a logical function-oriented process that identifies optimal equipment maintenance requirements based on reliability characteristics and operating conditions. Its goal is to eliminate PM tasks that do not add value to the maintenance process by using reliability data to adjust maintenance time intervals. John Moubray (1997, 28) defines RCM as “a process used to determine the maintenance requirements of any physical asset in its operating context”. This method was developed in the 1970s as a response to the traditional approach of scheduled maintenance that assumed that every system has a specific periodicity at which maintenance is required to prevent failure (Moubray 1997, 2–6). The application of RCM methods produces analysis that is useful in the development of a cost-effective PM program’s requirements (Blanchard and Fabrycky, Systems Engineering and Analysis 2011, 439). RCM seeks to answer seven basic maintenance questions (Moubray 1997, 7):

- What are the functions and associated performance standards of the asset in its present operating context?
- In what way does it fail to fulfil its functions?
- What causes each functional failure?
- What happens when each failure occurs?
- In what way does each failure matter?
- What can be done to predict or prevent each failure?
- What should be done if a suitable proactive task cannot be found?

RCM takes advantage of the predictive properties of equipment performance by using condition discovery methods such as scheduled inspections and rotating equipment vibration analysis. The RCM data produced during maintenance tasks is analyzed and used to identify or modify required task periodicity and execution. A well-implemented RCM strategy achieves greater equipment safety, performance, maintenance cost effectiveness, useful life, and better equipment database (Moubray 1997, 18-20).

RCM methods serve as the foundation for PM and condition-based maintenance (CBM) strategies.

Figure 1 displays a RCM decision diagram adapted from the work of Nowlan and Heap (1978). The decision tree shows a series of questions that should be asked to determine the consequences of an item's functional failure and the required PM to prevent the failure.

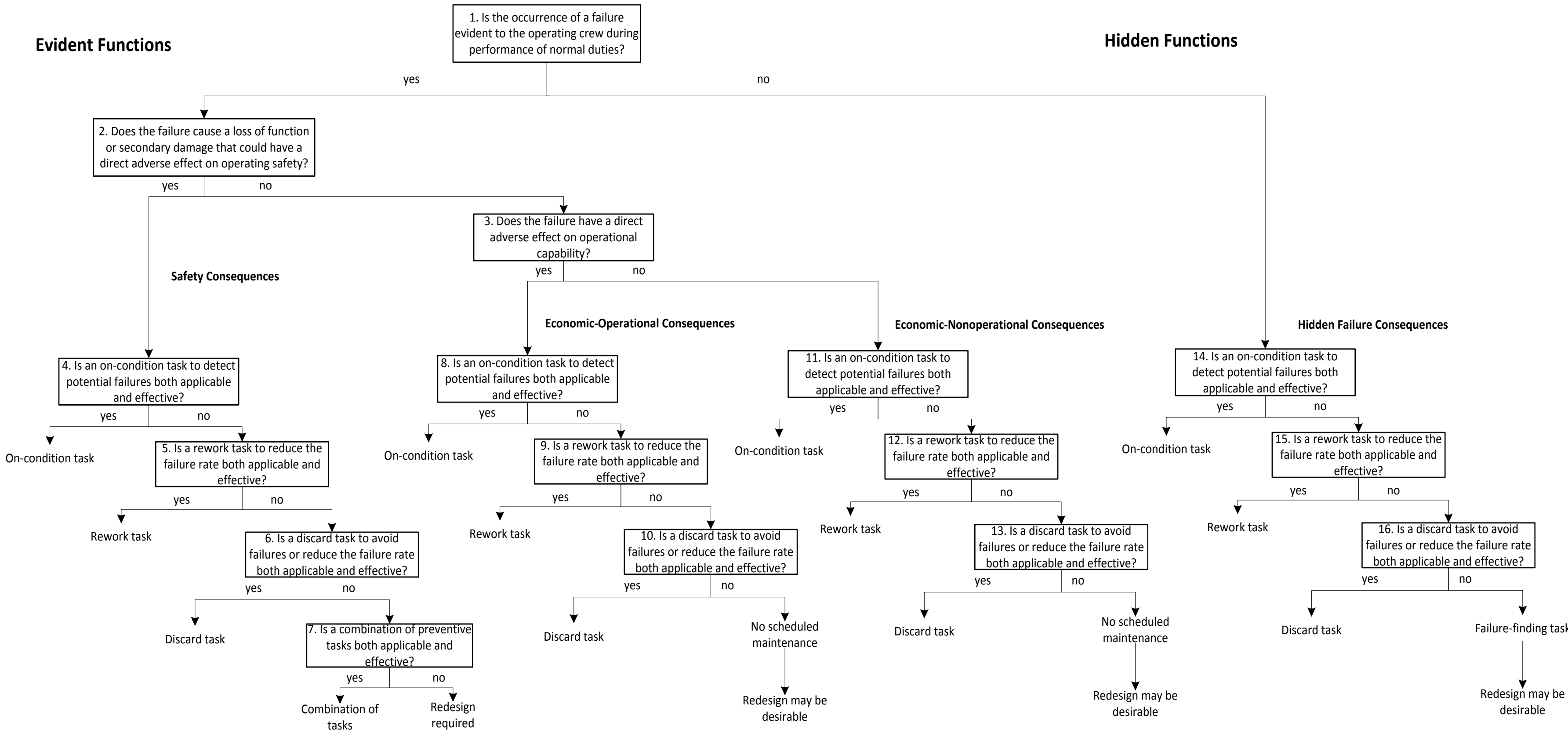

Figure 1. RCM decision diagram (after Nowlan and Heap 1978, 92–93)

(2) Preventive Maintenance

PM is a time-driven maintenance strategy based on calendar time, equipment operating time, or a number of cycles (Department of Defense 2008, 2-2). PM is intended to prevent unscheduled downtime or damage that may lead to a catastrophic failure. Surface Navy PM typically includes all scheduled maintenance actions that are performed to ensure a system is maintained in satisfactory operational materiel condition. PM actions and periodicity schedules are generated by system manufacturers and are adjusted throughout the system's lifecycle based on maintainer feedback and reliability analysis results.

There are three levels of PM. Onboard a legacy ship, organizational level PM actions are scheduled, planned, and performed by ship's force (SF). In the LCS program contractors are tasked with executing the organizational level PM actions. Intermediate and depot level PM actions are scheduled and planned by the ship's maintenance team which includes the Port Engineer (PE), the ship's commanding officer who is represented by the ship's maintenance and materiel officer (SMMO), and a representative of the activity executing the maintenance.

The Navy program of record used by ship's force in both LCS and legacy ships is a CMMS called SKED. SKED has been the surface Navy's CMMS since 2004. It creates, manages, and documents PM schedules for equipment (Antech Systems 2013).

PM strategy advantages include (Mobley 2002, 416):

- **Management:** PM allows managers to conveniently schedule personnel and equipment workload around the maintenance action.
- **Parts:** PM requires a smaller quantity of replacement parts are required in stock because the maintainer can predict the items required over a time period.
- **Availability**: A successful PM program keeps equipment operation within tolerance as it requires the system to be constantly maintained to a standard.

PM strategy disadvantages include (Mobley 2002, 417–418):

- **Potential to do damage:** PM may require performing unnecessary maintenance actions on equipment. There exists the potential for damage to be inflicted any time a system is touched for maintenance.

- **Infant mortality:** New replacement parts have a higher probability of failure.
- **Parts:** PM will result in perfectly functional parts to be replaced and discarded.

These PM advantages and disadvantages lists are not exhaustive but contain six of the most common characteristics that describe the PM approach.

(3) Condition-Based Maintenance Plus

CBM+ is a maintenance strategy derived from RCM. CBM+ uses real time or near real time system reliability sensor data, and other RCM methods to determine the best maintenance requirements for a system. According to the Defense Acquisition Guidebook (DAG), CBM+:

> Can be useful in cost effectively sustaining performance. It is the application and integration of appropriate processes, technologies, and knowledge-based capabilities to improve the reliability and maintenance effectiveness of Department of Defense (DOD) systems and components. At its core, CBM+ is maintenance performed based on evidence of need provided by RCM analysis and other enabling processes and technologies. CBM+ uses a systems engineering approach to collect data, enable analysis, and support the decision-making processes for system acquisition, sustainment, and operations. (Department of Defense 2013, 414)

The following is a selected list of goals resulting from successful CBM+ implementation. Each selected goal has an italicized portion that specifies the importance of an effective CMMS to manage equipment within a CBM+ approach:

- Enhance maintenance efficiency and effectiveness and *integrate all functional aspects of life cycle management processes* for materiel requirements, such as systems engineering, development, acquisition, distribution, supply chain management, sustainment, and modernization.(Department of Defense 2012, 5)
- Establish integrated, predictive maintenance approaches, which minimize unscheduled repairs, eliminate unnecessary maintenance, and employ the most *cost-effective system health management processes*. (Department of Defense 2012, 5)
- *Implement data collection* and analysis requirements... to measure equipment sustainment performance characteristics and supporting measures of

effectiveness throughout life cycle sustainment. (Department of Defense 2012, 5)

- Improve materiel reliability through the *disciplined analysis of failure data* to modify designs and operating practices to ensure equipment meets target performance standards within operational context. (Department of Defense 2012, 5)
- Optimize life cycle logistics processes and minimize mean downtime by providing *timely condition information, precise failure mode identification, and accurate technical data* that will expedite repair and support processes. (Department of Defense 2012, 5)

Figure 2 is an illustrated representation of the CBM+ concept and its relationship with CBM, RCM, and other supporting items.

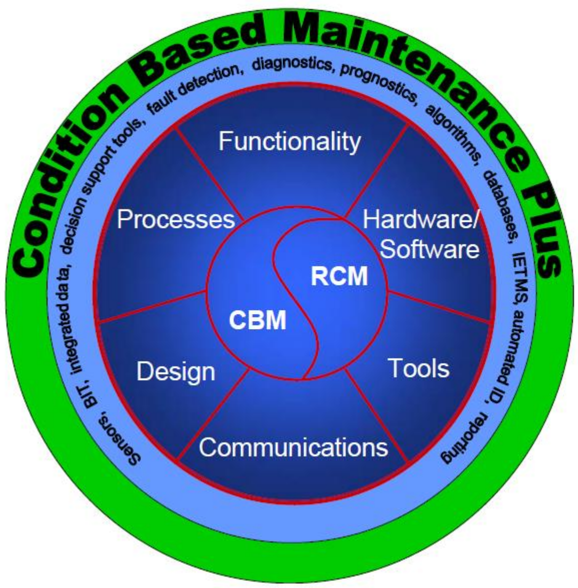

Figure 2. CBM+ overview (from Department of Defense 2008, 1-4)

In 2008, DOD policy established CBM+ as the primary reliability driver in the total life cycle systems management strategy. CBM+ is designed to meet the following DOD needs (Department of Defense 2008, 3–7):

- Equipment failure prediction
- Equipment condition holistic view
- Greater accuracy in failure prediction

- Reduce the cost of ownership
- Improve equipment and component reliability
- Reduce equipment mean down time (logistics responsiveness)
- Optimize equipment performance (availability)

CBM+ implementation requires embedded sensors for equipment monitoring and data transmission. CBM+ implementation early in a ship's lifecycle provides early visibility into equipment performance trends that may result in failures. The equipment performance history developed from an early implementation could potentially lead to improving maintenance and lower maintenance costs. Since the goal of CBM+ is to maintain based on evidence, the issue of what constitutes evidence may involve more than a sensor output. Other factors include the analysis of the equipment data history and how well the data is managed.

b. Corrective Maintenance

Corrective maintenance (CM) is reactive maintenance. It includes all unscheduled maintenance actions executed as a result of system malfunction, failure, or deterioration (Navy Personnel Command 2013). CM scheduling and planning urgency is determined by the severity and emergence of the casualty and its impact on the ship's mission. The emergent nature of CM work usually results in high labor costs and in unexpected system downtime. Depending on a system's complexity, the amount of time spent isolating, finding, troubleshooting, and correcting a failure during CM can range from minutes to days and even weeks. Figure 3 displays a general flowchart of the CM cycle.

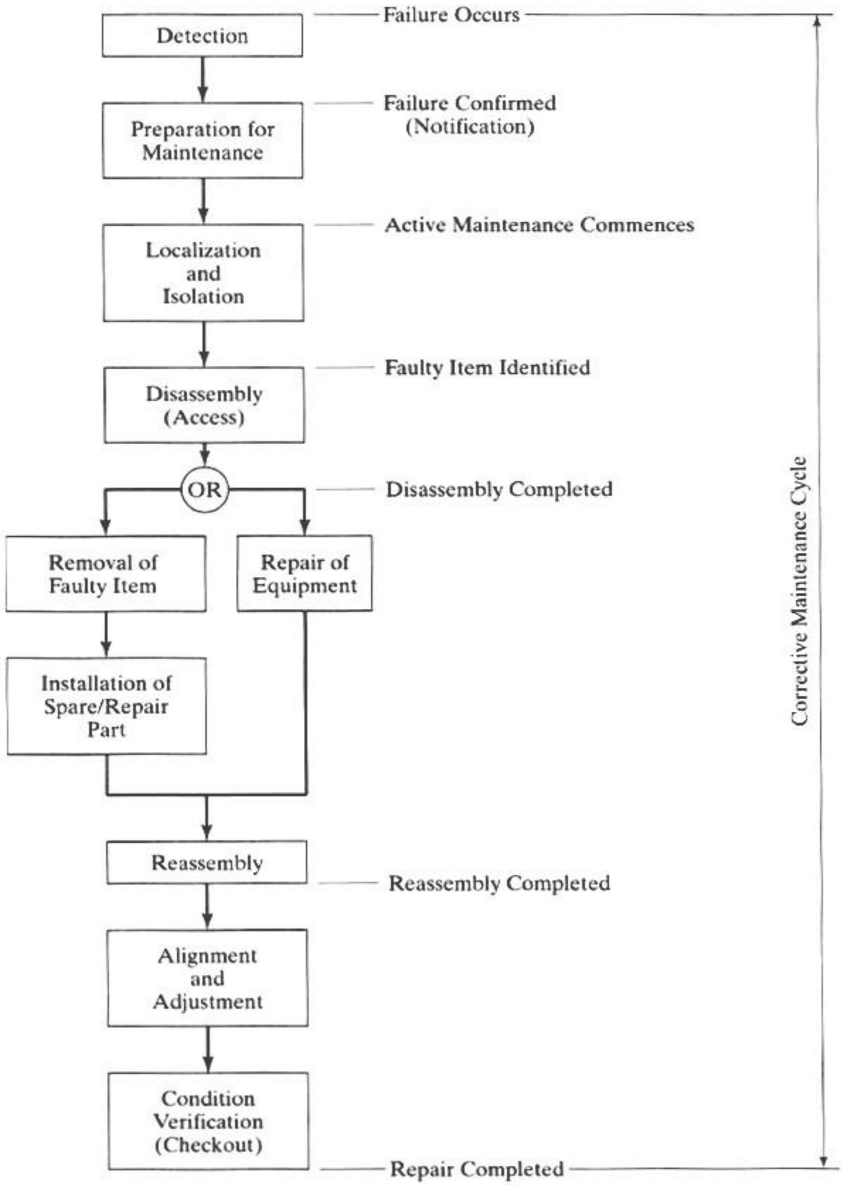

Figure 3. Corrective maintenance cycle (from Blanchard 2004, 59)

2. Maintenance Overview Summary

Figure 4 is a graphical summary of the DOD maintenance approaches used in the Navy. The two overarching maintenance categories are proactive and reactive. Proactive maintenance splits into preventive and predictive strategies, both of which are based on RCM.

Maintenance Approaches				
	Reactive	Proactive		
Category	Run-to-fail	Preventive	Predictive	
Sub-Category	Fix when it breaks	Scheduled maintenance	Condition-based maint.-diagnostic	Condition-based maint.- prognostic
When Scheduled	No scheduled maintenance	Maintenance based on a fixed time schedule for inspect, repair and overhaul	Maintenance based on current condition	Maintenance based on forecast of remaining equipment life
Why Scheduled	N/A	Intolerable failure effect and it is possible to prevent the failure effect through a scheduled overhaul or replacement	Maintenance scheduled based on evidence of need	Maintenance need is projected as probable within mission time
How Scheduled	N/A	Based on the useful life of the component forecasted during design and updated through experience	Continuous collection of condition monitoring data	Forecasting of remaining equipment life based on actual stress loading
Kind of Prediction	None	None	On- and off-system, near-real-time trend analysis	On- and off-system, real-time trend analysis

Figure 4. Range of maintenance approaches (from Department of Defense 2008, 2–3)

B. COMPUTERIZED MAINTENANCE MANAGEMENT SYSTEMS

1. Overview

CMMS programs are fundamental database tools that assist maintenance activities in decision making regarding planning, management, and administration of maintenance actions required in a CBM+ strategy. The CMMS is an interactive equipment parameter and condition database that can receive data input from users or from sensors and meters. The equipment data is stored as a system-specific maintenance history that may be used by decision makers to detect trends and perform analysis.

CMMS programs typically interface with users through customizable modules chosen based on the maintenance data requirements. Some of the most common CMMS modules perform data analysis related to (Wireman 2009, v):

- Preventive maintenance
- Parts inventory
- Parts procurement

- Work-order management
- Labor costs
- Material costs
- Contracting cost

Figure 5 is an illustration of the traditional core CMMS activities. The illustration displays the division of CMMS activities into four main activities that split into 18 sub-activities.

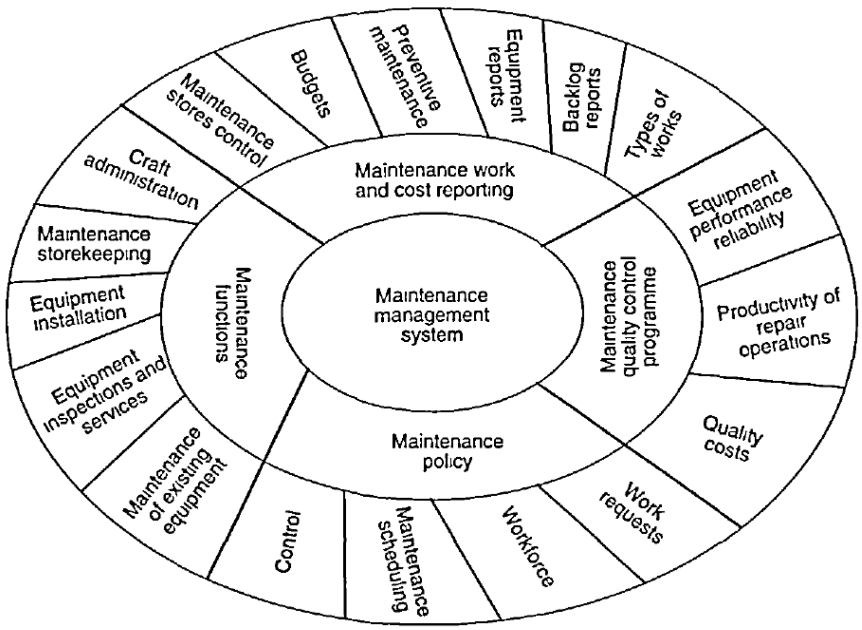

Figure 5. Typical CMMS activities (from Raouf, Ali and Duffuaa 1993, 39)

Over the last 20 years CMMS software has continuously improved to provide better functionality to the user. The CMMS aspects that have most evolved are related to application integration, planning and scheduling capabilities, analytical tools in support of RCM and failure analysis, and integration with mobile technology (Berger 2011). The effective implementation and use of CMMS software may result in increased labor productivity, increased equipment availability, longer equipment useful life, reduced inventory costs, and an increase in overall system productivity (Bagadia 2006, 111-112). A CMMS may help accomplish this by collecting and displaying essential maintenance

information to assist decision makers to better manage the trends and requirements of a CBM+ maintenance approach.

Many corporations that utilize a CMMS as part of their maintenance program fail to use the system correctly resulting in wasted funds, time, and effort. A 2005 survey shows that 94% of 300 companies fail to reap the full benefits of their CMMS program (Bagadia 2006, 234). The most common reasons for unsuccessful CMMS implementation include:

- Limiting the CMMS to act as a database instead of an analysis tool (Arnold 2006)
- Implementing unnecessary and unmanageable modules (Arnold 2006)
- Sacrificing training for time and cost savings (Arnold 2006) (Bagadia 2006, 235)
- Wrong CMMS selection (Bagadia 2006, 196)
- Failure to populate the CMMS with system data such as parts inventory (Arnold 2006) (Wireman 2009, 129-130)
- Poor interface with other management software (Arnold 2006) (Wireman 2009, 128)
- Failure to develop a CMMS implementation plan (Hemming and Davis 2003)

Many corporations mistakenly approach CMMS technology as a ‘simple and quick fix’ by failing to realize that the successful implementation of the maintenance system relies on process discipline, support systems, and organizational capabilities (Autin 1998, 33-35). “Top organizations start by understanding their maintenance environment. They analize their business needs, match a system and processes to those needs, and apply formal processes to select and implement the new system” (Davis and Mikes 2006). Succesful implementation and utilization of a CMMS is preceded by the performance of a justification analysis, a thorough system selection process, and a systematic implementation process (Wireman 2009, 3–11).

a. Justification Analysis

A study to justify the necessity of a CMMS requires an identification of needs based on current practices, an evaluation of effectiveness within the organization’s maintenance process and identification of improvement opportunities (Bagadia 2006, 103–105).

In 2000, the Plant Maintenance Resource Center polled 77 CMMS using companies about the factors considered in choosing a CMMS. Table 1 lists the top answers provided. According to the survey, only 25 companies chose a CMMS to meet a need to improve maintenance performance.

Table 1. Factors considered in justifying CMMS implementation (from The Plant Maintenance Resource Center 2009)

What was the main reason that your workplace changed CMMS, or implemented a new CMMS?		
Reason	**Responses**	**% of Total**
To improve maintenance performance	25	28.7%
Improved functionality and features	16	18.4%
To integrate the Maintenance system with other systems	9	10.3%
Don't know	8	9.2%
Year 2000 compliance problems	7	8.0%
Vendor no longer supported our old CMMS	2	2.3%
To comply with company standards	2	2.3%
To use newer technology	1	1.1%
Other	7	8.0%

The reasons provided by these corporations to justify the implementation of a new CMMS show the variety of organizational needs the program is required to satisfy. A company that justifies new CMMS implementation based on improving maintenance performance should measure implementation effectiveness using different factors than one that chooses a new CMMS to integrate different systems. There is no standard set of MOEs that will capture a CMMS implementation's fitness-for-purpose for all different users.

b. System Selection

Proper CMMS software selection is instrumental for the successful implementation and use of the tool. The correct implementation of COTS CMMS software requires a needs analysis to ensure that the chosen program and its implementation achieve the intended mission. The first step in the selection process is to ensure that the company's needs, scope, goals, and objectives, as they relate to CMMS, are well defined (Bagadia 2006, 121-133).

This step helps prevent selecting a CMMS based on the desire to obtain a "silver bullet to magically fix inefficiency and ineffectiveness" (Autin 1998, 33).

The following are some of the most commonly evaluated criteria while selecting a CMMS:

- *Ease of learning* – Software should include training modules and instructions documentation. (Bagadia 2006, 129)
- *Ease to use* – The software should be menu driven, with customizable screens, error handling help, and useable by maintainers with no programming experience. (Bagadia 2006, 129)
- *System limitations* – Particularly the system's ability to properly process and analyze the required amount of data without significant degradation in performance. (Bagadia 2006, 127)
- *Software flexibility* – The software should allow for expansion and modification based on user needs. (Bagadia 2006, 127)
- *Software compatibility* – The software should be compatible with the user's operating system. (Bagadia 2006, 127) (Caviedes and Knecht 2006) (Ouellette 2005)
- *Interface capabilities* – The software should interface with other maintenance management system the user employs. (Bagadia 2006, 127) (Caviedes and Knecht 2006)
- *Security* – Software should provide a backup facility to prevent any data loss. (Bagadia 2006, 128)
- *Vendor stability and technical support for implementation* – The software vendor should have proven field longevity and provide technical support in areas to include: update releases, engineering consulting, data collection, data entry, training, and general implementation. (Ouellette 2005) (Bagadia 2006, 130)
- *System cost* – To include cost of core program and expandable modules. (Ouellette 2005)

c. CMMS Implementation

CMMS implementation involves a series of steps that include installing and configuring the software, fully defining, reviewing, and implementing "all workflow processes, data-recording requirements, management reports, and performance metrics" (Bertolini 2009). Figure 6 is a flowchart for a typical CMMS implementation process.

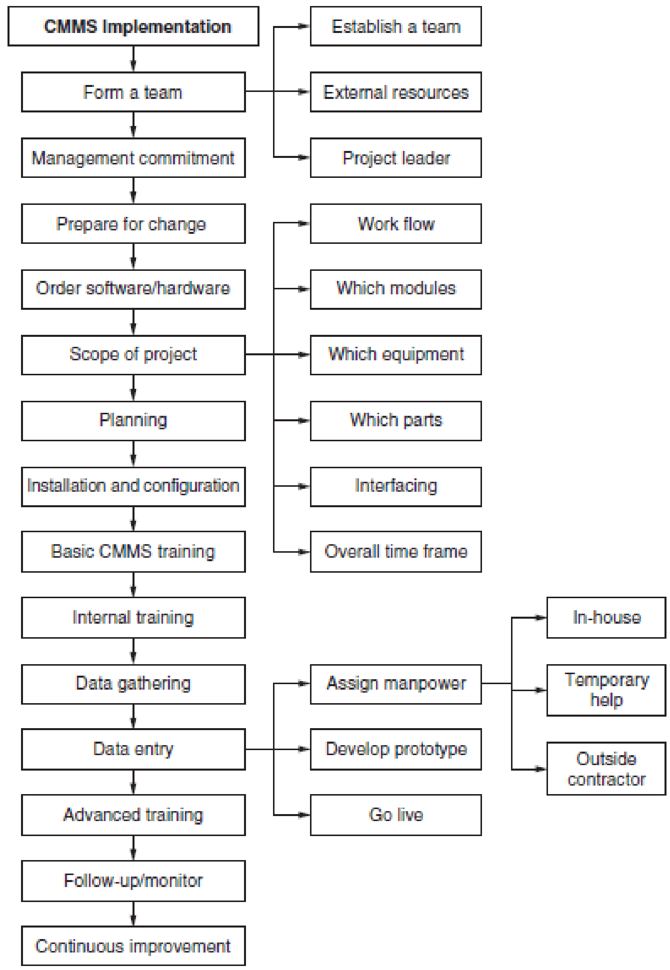

Figure 6. CMMS implementation flowchart (from Bagadia 2006, 199)

The following steps are the most commonly addressed regarding CMMS implementation (Wireman 2009, 107-121):

- *Developing a project plan and determining resource requirements* – Establish implementation teams with representatives from each department affected by the CMMS. Establish task-oriented teams responsible for the resources and tasks associated with their portion of the CMMS implementation.
- *Updating all current records* – Ensure the CMMS data is factual and up-to-date and in the correct format for input to the system. Typical equipment data includes: general information, nameplate data, inspection reading limits, financial information, and asset history.
- *Software installation* – Load the program on the required computers and make sure it works correctly.

- *Data entry & migration* – Input the information from the current data keeping system into the CMMS program database. Special attention needs to be placed on cataloging and data accuracy.
- *System introduction and updates* – Present the CMMS program to the users appropriately in a manner that enables them to use it as required.
- *CMMS training* – Often overlooked, training is indispensable for the correct and effective use of the CMMS.

Any CMMS program may be limited to act as a maintenance database if not integrated within the organization correctly. Figure 7 is DOD's representation of the CBM+ concept and its infrastructure building blocks. A well-implemented CMMS program interacts with all CBM+ infrastructure blocks.

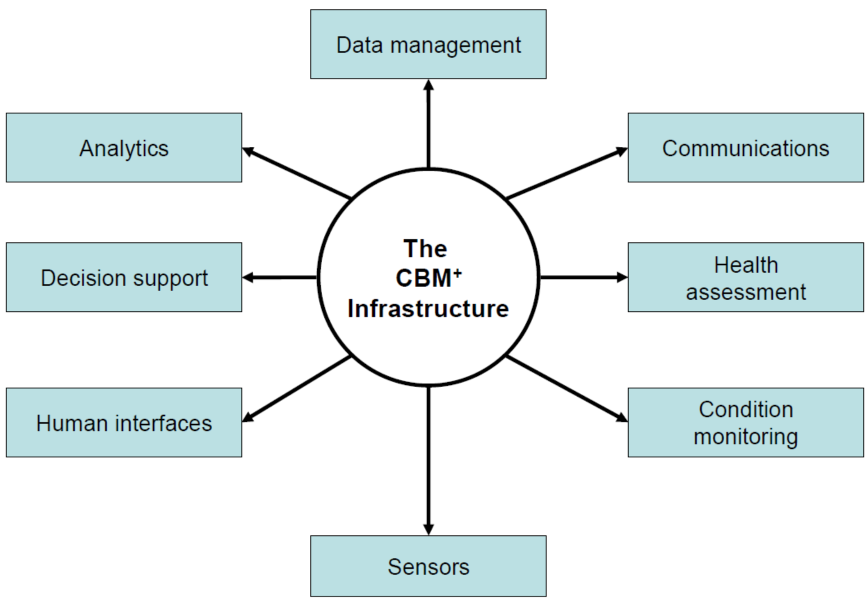

Figure 7. CBM+ infrastructure (from Department of Defense 2008, 3-18)

CMMS introduction and training are two key steps during CMMS introduction as a new maintenance tool to a large maintenance organization. A CMMS can only perform effectively when the users input enough timely accurate data to build a history that may indicate equipment trends. Building an accurate history of equipment performance may become difficult when the CMMS users are resistant or poorly trained on how to operate the program.

2. CMMS Requirements in Official CBM Policy

a. Chief of Naval Operations (CNO) CBM Policy

The CNO's CBM policy, released in December 2007, establishes the policies and responsibilities related to the implementation of CBM on naval assets. The instruction mandates a fleet-wide transition to incorporating CBM strategies "to the maximum extent possible" into all maintenance programs while continuing to employ RCM methods for maintenance planning (Chief of Naval Operations 2007, 1). The policy requires training for maintenance managers and technicians as well as the integration of CBM with a data collection system.

> CBM enabling information systems (data collection and information analysis) shall be integrated with maintenance management and logistics support information systems. The impact of information systems data collection, processing, and warehousing requirements on afloat and ashore resources shall be considered in system design, development, and life-cycle planning. (Chief of Naval Operations 2007, 3)

The CNO CBM policy explicitly identifies the importance of a suitable information system for the success of CBM implementation.

b. NAVSEA CBM+ Policy

The Naval Sea Systems Command (NAVSEA) is assigned to build, deliver, and maintain Navy ships. NAVSEA instruction 4790.27A, released in May 2013, establishes the policy and responsibilities for RCM, CBM, and CBM+ integration into the ship's lifecycle maintenance strategy. The instruction makes CBM+ the approved maintenance strategy for ships, ship systems, and equipment and it also mandates the use of software to conduct CBM+ analysis and other functions.

> Ensure equipment and systems performance and reliability analysis software and display systems provide timely actionable data against the predictive failure risk models during acquisition and sustainment. (Naval Sea Systems Command 2013, 10)

NAVSEA policy explicitly identifies the need for software to meet the fleet's CBM+ needs.

C. CMMS USE IN THE LCS PROGRAM

The LCS program office tasked two civilian contractors with executing maintenance management including the planning and execution of all intermediate, depot, and a large percentage of the organizational level maintenance. Both contractors have independently implemented the use of an IBM developed CMMS in support of the CBM+ strategy. Navy maintenance representatives do not provide specific guidance defining how the contractor shall use CMMS in support of CBM+.

The CMMS is used as a maintenance database and PM scheduling tool. CMMS use varies between contractors. Each contractor uses the CMMS in accordance with their independently developed maintenance approach. Some differences in their CMMSs involve equipment coverage, program applications, data generation, and general program usage. Maintenance managers and supervisors manually input the equipment status, maintenance history, and maintenance plans into the CMMS. Integration of the current CMMS with Navy legacy maintenance programs has been challenging.

D. CBM+ MAINTENANCE MANAGEMENT SYSTEM STAKEHOLDERS

CBM+ maintenance management system stakeholders are individuals and organizations interested in the successful employment of the CMMS as a CBM+ support system. Navy maintenance stakeholders include government and civilian organizations and managers involved in the maintenance process throughout the life of a ship.

a. Department of Defense

DOD establishes CBM+ instructions and directives for military departments and defense agencies.

b. Department of the Navy

The CNO establishes policies and instructions for CBM+ implementation and integration onboard naval ships, submarines, aircraft, equipment, and infrastructure. NAVSEA is the Department of the Navy (DON) command responsible for promulgating, updating, and implementing maintenance policy and instruction.

c. Program Office

Program office personnel include government decision makers responsible for all aspects of life-cycle management to include maintenance planning, execution, and budgeting.

d. CMMS Power Users

Power users include government personnel and civilian contractors who use advanced CMMS features and modules to perform their primary tasks. Power users are primarily involved in the business and execution aspect of maintenance and are not necessarily programmers. Their tasks include supply management, data analysis, maintenance procedure development, and other related to information technology (IT).

e. Maintenance Managers

Maintenance managers include government and contractor personnel responsible for maintenance planning, execution, reporting, and budgeting.

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III. LITERATURE REVIEW: MEASURES OF EFFECTIVENESS

Measures of effectiveness (MOE) are an integral systems engineering (SE) and general management tool, yet a universal MOE definition, across or within management disciplines, does not exist. MOEs are usually discussed in SE, business, and management literature. Most of the engineering and non-engineering literature addressing MOEs lacks depth in their explanation of MOE development. MOEs are generally described as sets of required measurements that aid in determining how well something achieves its operational purpose. Most sources describe the importance of MOEs, the features that make good MOEs, and they often provide insight into their applications. However, there is a lack of literature seeking to present a repeatable MOE development method or framework.

Roedler and Jones (2005, 9) define MOEs as "operational measures of success that are closely related to the achievement of mission or operational objectives". In this analysis MOEs are a subset of technical measures used to develop technical performance measures providing a system's technical resolution and insight. They are identified by the stakeholder early in the acquisition process with the goal of providing insight into specific operational requirements. An illustration of these interdependent measures can be seen in Figure 8.

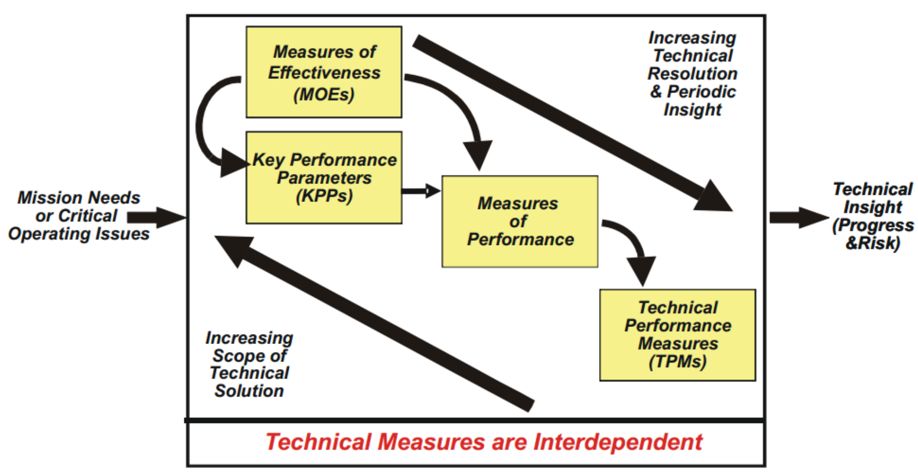

Figure 8. Technical measures relationships (from Roedler and Jones 2005, 15)

Roedler and Jones provide a set of guidelines that describe the characteristics that make a well selected MOE advantageous to the user and the analyst. A summary of these guidelines is included below in Table 2.

Table 2. MOE selection guidance (from Roedler and Jones 2005, 36)

MOE
Provides insight into at least one operational objective or mission requirement
MOEs should not be strongly correlated: provide insight into different aspects of the operational alternative
Select and define in the context of the operational objective : no predefined MOEs/values
Select and define independent of the alternatives at hand : represent an independent means to collectively evaluate the alternatives
Select only a few MOE/MOPs : may be an order of magnitude more TPMs
Each KPP should have an associated MOE or MOP

Roedler's analysis provides a useful qualitative approach to MOE development but it lacks a methodical framework. His guidelines are useful to revisit during the MOE development process because they are good descriptors of verifiable measurements.

Wireman addresses five related performance indicators for a corporation. Like Roedler, Wireman considers MOEs to be part of a larger framework of measures. The complete framework becomes the performance indicator pyramid. Each level in the pyramid contains performance indicators at five different levels of the corporation. The principal performance indicators are defined by corporate management at the pyramid's apex. All other performance indicators in the corporation are shaped by those at the top of the pyramid. Wireman argues that when the indicators are developed from the bottom up they may

become conflictive and unsupportive of the corporate vision. The performance indicator pyramid is displayed in Figure 9.

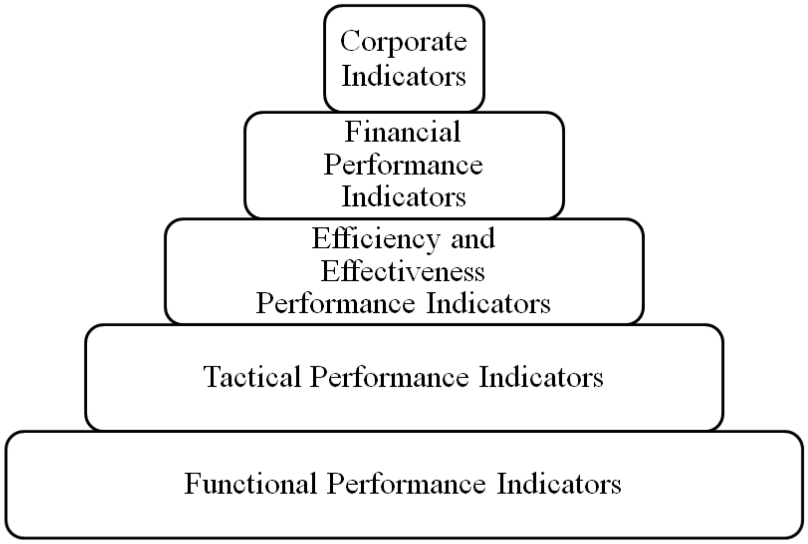

Figure 9. Wireman's performance indicator pyramid (after Wireman, Developing Performance Indicators for Managing Maintenance 2005, 220)

Although a relationship exists between the five levels in the pyramid, the middle and bottom levels address the traditional MOEs. The middle level links the measurements of efficiency and effectiveness. Efficiency describes how well a task is performed while effectiveness describes how well the task meets its goals and requirements. Wireman emphasizes using a system's output measures instead of the input measures to develop the results required to determine the efficiency and effectiveness of a task. Output measures are associated with efficiency and effectiveness indicators. Input measures and process measures seek to describe workload. In this lean-derived approach the effectiveness indicators are chosen to support financial indicators seeking to reduce waste, expense, and effort (Wireman, Developing Performance Indicators for Managing Maintenance 2005, 210).

Wireman's indicators are expressed as percentages or ratios. Some of the work-order system effectiveness indicators include percentages of work distributon by type of work-order. Wireman expresses some of these percentages as (Wireman, Developing Performance Indicators for Managing Maintenance 2005, 211):

$$\frac{\text{Emergency Work Orders}}{\text{Total Work Orders}}$$

$$\frac{\text{Preventive Work Orders}}{\text{Total Work Orders}}$$

$$\frac{\text{Corrective Work Orders}}{\text{Total Work Orders}}$$

The functional performance indicators provide ratios used to evaluate the performance of specific maintenance functions. Some of the CMMS functional performance indicators include (Wireman, Developing Performance Indicators for Managing Maintenance 2005, 217–218):

$$\frac{\text{Total Number of Equipment Items in CMMS}}{\text{Total Number of Equipment Items in the plant}}$$

$$\frac{\text{Total Number of Part Items in CMMS}}{\text{Total Number of Part Items in the plant}}$$

$$\frac{\text{Total Number of PM tasks}}{\text{Total Number of Equipment Items in the plant} \times 3}$$

Wireman provides close to 100 performance ratios that a maintenance manager may use to develop an initial set of performance indicators. Each ratio measures performance at a different level in the corporation. However, Wireman fails to provide explanations as to the significance or development of these ratios as they determine levels of performance. Using performance indicators without justification makes an organization data rich but information poor. Wireman also fails to address stakeholder needs or requirements elicitation. One could assume that the corporate indicators at the pyramid's apex may define needs and requirements but this approach may lead to MOE development based on wants instead of needs. Using corporate indicators in MOE development may result in inappropriate measurements that are solution specific, alternative specific, and dependent on corporate opinion.

Stevens describes MOEs in the context of operational testing and evaluation (OT&E). In OT&E, MOEs are defined as "any set of criteria established to determine the resolution of a critical issue" (Stevens 1986, 54). Stevens' MOE development rules are specific for a testing environment but remain useful and transferable for other uses. OT&E MOEs are tied to critical issues which may be broken down into lower level elements to provide combinable specific data. Stevens' testing viewpoint permits the use of MOEs to understand a system's test results and develop a set of conclusion data that may be used for other system's tests.

Stevens lists the following characteristics to describe a good MOE (Stevens 1986, 55):

- The MOE should be relevant.
- The set of MOEs should be complete.
- The MOE should be precisely defined.
- The MOE sets should be mutually exclusive.
- The MOE should be expressed in terms that are meaningful to testers and developers.
- MOE meaning should not be open to interpretation with the passage of time.
- MOE inputs should be measureable.

Stevens also provides seven MOE development ground rules (Stevens 1986, 55–56):

- There should be one MOE for each mission capability.
- MOE weights shall be assigned by decision makers.
- Fully define the mission and scenario before collecting measurements during testing.
- Measurements should not interfere with system operation.
- State MOE quantitative measurements as probabilities.
- All qualitative measurements should use the same standard.
- When recording system failures during testing include both: faulty system and hardware failures.

Many of Stevens' MOE characteristics and development ground rules echo those discussed by Roedler. But like Roedler, Stevens succeeds in describing good MOEs and their relevance to an application but fails to present a development method or framework.

Sproles acknowledges the lack of both a universal MOE definition and a method to formulate them. MOEs and measures of performance (MOP) are commonly used as interchangeable terms in management and engineering literature. Sproles uses developmental viewpoints to differentiate between MOEs and MOPs.

> The distinction between effectiveness and performance shows that MOEs and MOPs are formulated from different viewpoints. An MOE refers to the effectiveness of a solution and is independent of any particular solution; an MOP refers to the actual performance of an entity. The relationship between the two types of measures can be described using the analogy of the relationship between effectiveness and efficiency. Effectiveness is how well something does its job. Efficiency is how well something does what it is doing. Therefore, efficiency can be high while effectiveness is low or even zero. Something can be done well even though it is the wrong job which is being done. An MOE will indicate a property which a potential solution must possess in order to meet a need: An MOP will tell what something is capable of doing, even if this is not necessarily what the stakeholders want it to do. The difference between effectiveness and performance as applied to a solution to a need is that effectiveness is a quality of fitness for service or of producing the results for which it was intended. Performance is the quality of .doing something, and doing something does not necessarily indicate fitness for service. (Sproles, Coming to Grips with Measures of Effectiveness 2000, 56–57)

Sproles' places stakeholder needs and requirements at the center of developing a process that captures how well a system performs its mission. The process begins with stakeholder requirements elicitation. These requirements will provide the characteristics to determine the effectiveness of a system and will consequentially influence the system selection decisions. This method combines the stakeholder's input and the stakeholder viewpoint to identify a mission to frame the MOEs. Like Stevens, Sproles explains that MOEs need to address critical operational issues (COI) exclusively. A COI is "an emergent property that the system must have in order to perform its function [and] that a solution to a need must possess in order to meet the need" (Sproles, Formulating Measures of Effectiveness 2002, 256-257). Developers need to identify the system's critical items of interest before drafting the MOEs to help determine the system's essential operational attributes. MOE drafting requires creative and knowledgeable people with good management techniques to provide answers and heuristics that can be honed into testable and measurable

statements that address the COIs. Once established, the MOEs shall be evaluated, iterated, and revised (Sproles, Formulating Measures of Effectiveness 2002, 258-259).

Sproles' MOE development process is illustrated in Figure 10.

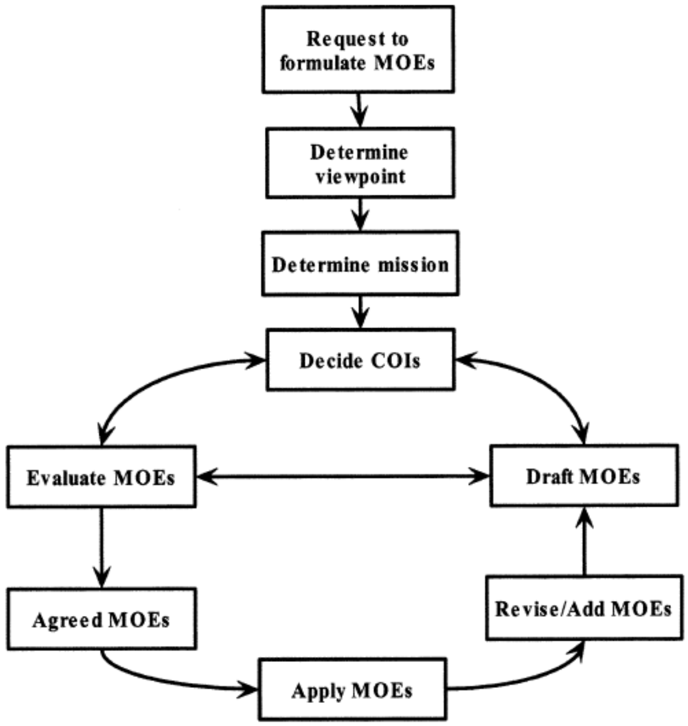

Figure 10. MOE development process (from Sproles, Formulating Measures of Effectiveness 2002, 255)

Once the COIs are decided the MOE follows an iteration loop to ensure it remains relevant to the system's measurements. However, if the COI is decided by a viewpoint or mission that is no longer relevant or was originally mistakenly determined the irrelevant MOE will be stuck in the iteration loop and will create waste.

Sproles' MOE formulating process serves as a good starting point for a way towards a methodical MOE development approach; however it is too subjective to the input of a singular stakeholder because it narrows the solution trade space by possibly limiting MOE selection decision to one viewpoint. A narrow solution trade space may lead to missing alternatives that may meet the needs. Sproles links MOEs to COIs and COIs to needs but

provides no guidance in differentiating between a need and a want. Although it has some faults, Sproles' stakeholder centric MOE development method is a step in the right direction of establishing a repeatable method to develop MOEs.

Leibowitz discusses MOEs from a metaphysical operation analyst's viewpoint. His approach resonates with Sproles' call for creativity and heuristics in the formulation of MOEs. "A measure of effectiveness resembles a moral principle in that its validity cannot be established by reason alone. We must make a value judgment. We must play it by feel" (Leibowitz 1958, 127). Leibowitz' calls his qualitative approach to choosing MOEs the method of dynamic compromise. The method of dynamic compromise is comprised of four steps:

- Obtain an approximate measure of the system's effectiveness using the limited understanding of the supersystem (Leibowitz 1958, 130).
- Adjust the measure and relate it to the system's elements (Leibowitz 1958, 130).
- Readjust the measure until it is satisfactory to the decision maker (Leibowitz 1958, 130).
- Readjust the measure until the projected study does not exceed time and effort deadlines (Leibowitz 1958, 130).

Once the analyst readjusts the fourth step measure they compare it to the true needs of the system in question. This last step is where the analyst uses his "feel". If the fourth measure is not close to a true need the analyst has five courses of action:

- Learn more about the supersystem (Leibowitz 1958, 130).
- Learn more about the system itself (Leibowitz 1958, 130).
- Talk the decision maker into revising his interpretation (Leibowitz 1958, 130).
- Extend the scope of the study (Leibowitz 1958, 130).
- Cancel the study (Leibowitz 1958, 130).

Leibowitz' method of dynamic compromise is simple and maintains the development process grounded on the fact that an MOE "must be reasonably close to representing the true purpose of the system. If it is not then all the linear programming and all the game theory in the world will not save us from optimizing auto assembly lines so as to provide the maximum number of coffee breaks per hour" (Leibowitz 1958, 130).

Essawy and Zein-sabatto define MOEs and MOPs specifically for CBM systems. There is a need for CBM technology developers to develop a set of universal measures for competing systems comparison, suitability determination and, fitness-for-purpose evaluation. Essawy and Zein-sabatto use the MOE and MOP terms almost interchangeably, only differentiating between them by the scope of the measured attribute. MOEs address those measurements specific to a system while MOPs address the measurements specific to subsystems (Essawy and Zein-Sabatto 2000, 303).

Essawy presents and analyzes several mathematical expressions representing CBM system variables considered. These variables serve as inputs for functions that describe the MOPs or MOEs. Some of Essawy's essential variables have been selected and are explained below.

Success and failure rates measure the rate of a system's successful function performance. I_S, I_F, and I_T are the number of success, failure, and total instances respectively (Essawy and Zein-Sabatto 2000, 304).

$$\text{Success Rate} = \frac{I_S}{I_T}$$

$$\text{Failure Rate} = \frac{I_F}{I_T}$$

The time delay is the time required by a system to perform its intended function. T_f and T_i are the final and initial recorded times respectively (Essawy and Zein-Sabatto 2000, 304).

$$\text{Time Delay} = T_f - T_i$$

Reliability measures the frequency of system failures. The average extent is the average partial system failure. Average extent is "a summation of the extent of all of the individual partial failures divided over the number of partial failures multiplied by the maximum predicted partial failure extent" (Essawy and Zein-Sabatto 2000, 304). The function variables are the total number of partial failures (n) and the extent of partial failure at each incident (A_i) (Essawy and Zein-Sabatto 2000, 304).

$$\text{Average Extent} = \frac{1}{n}\sum_{i=1}^{n}\frac{A_i}{Max(A_i)}$$

$$\text{Reliability} = e^{-3.5\,(\text{Failure Rate} + \text{Ave Extent})}$$

Robustness measures the ability of a system to function satisfactorily in the presence of changing conditions and inputs. $I_{\#}$ are the number of instances in which a changing condition was introduced. The index variables, *i, j, m,...z,* are the various conditions that can introduce change and inputs into the system (Essawy and Zein-Sabatto 2000, 305).

$$\text{Robustness} = \frac{1}{I_1 + I_2 + I_3 ... + I_N}\sum_{i,j,m,...z=1}^{I_1 + I_2 + I_3 ... + I_N}(\text{Success Rate})_{i,j,m,...z}$$

Essawy's method uses the results of these variable functions to calculate a quantitative MOE or MOP. The resulting calculations are further manipulated using one of three approaches:

- Weighed sum: Calculates an MOE/MOP figure by using the sum of the products of the calculated variables by an assigned weight corresponding to the variable's relevance in determining successful or effective performance (Essawy and Zein-Sabatto 2000, 307).
- Fuzzy logic: This method uses the input variables to emulate human-decision making methods (Essawy and Zein-Sabatto 2000, 308).
- Neural network system: The MOE/MOP figure is estimated by measuring the "output of a feed-forward backpropagation neural network" using the calculated variables as inputs. Essawy does not provide an example of this method (Essawy and Zein-Sabatto 2000, 308).

Essawy and Zein-sabatto present replicable methods to calculate MOEs and MOPs. Like Wireman's, this method succeeds in providing guidance of possible effectiveness and performance indicators but fails in providing a reason as to why these indicators are relevant. Essawy's research also leaves out the stakeholder needs and requirements. Also, because Essawy interchanges the terms MOE and MOP, some of his variables become so generic that they fail to capture a system's success in meeting a set of needs.

Langford defines MOEs as "the single-most often touted and applied method of thought of how well one is doing" (G. Langford, Building the Determinants of Technology Effectiveness 2014,3). Effectiveness determination depends on the identification of significant measures of causality, the interpretation of measurements, and the measurement

viewpoints; these three factors allow for the determination of functions, processes, effects, and data evaluation as they relate to measurable effectiveness. Langford proposes developing MOEs using an integrative framework (G. Langford, Building the Determinants of Technology Effectiveness 2014, 4-7). The framework is a 3×3 grid composed of an objective frame and a subjective frame. The objective frame captures the product or service; the subjective frame captures the management process to satisfy the product or service. The intersections of frame elements create nine cardinal points that represent the MOE domains. These cardinal points are the interaction between a product's constituents that determine overall system effectiveness. An MOE set that captures all the necessary objectives required for success shall cover all domains in the framework. Figure 11 displays the framework's two frames, the domain descriptions, and domain elements.

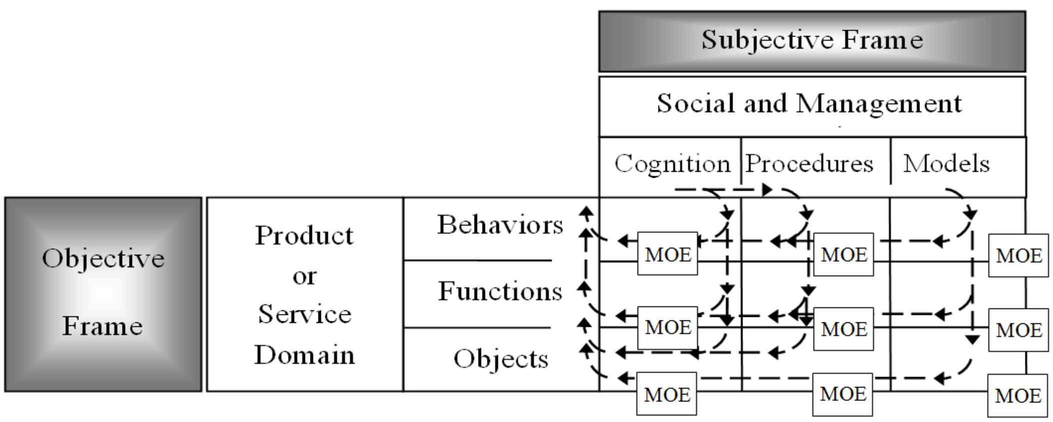

Figure 11. Integrative framework (from G. Langford, Determinants of Deterrence Effectiveness 2014, 7)

The use of this framework as an MOE development tool emphasizes the process-object relationships used to evaluated the system's fitness-for-purpose. As illustrated in figure 12, fitness-for-purpose is the real knowledge required to determine how well a system satisfies its objective (G. Langford, Building the Determinants of Technology Effectiveness 2014,8).

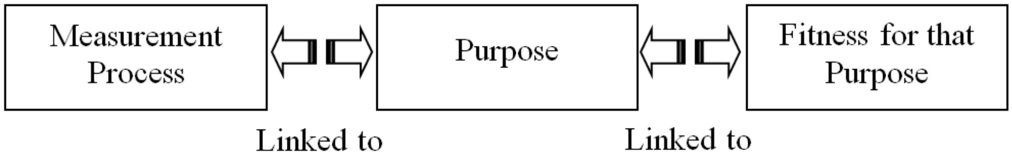

Figure 12. Linkage between MOEs and fitness-for-purpose (from G. Langford, Building the Determinants of Technology Effectiveness 2014, 8)

Langford's MOE development framework does not dictate a set of suggested measurements adaptable to any system. The MOE set produced by this framework is unique in that it addresses the specific requirements to satisfy the system managerial and operational specific needs. Langford's method also calls for periodic feedback and iteration to ensure effectiveness measurements remain accurate as the system's objects interactions change with time and experience.

IV. METHODOLOGY

The computerized maintenance management system (CMMS) measures of effectiveness (MOE) were developed using traditional system engineering (SE) concepts and a nine-step method for characterization. The SE concepts are standard in the identification of user needs, analyzing system requirements and functional requirements.

A. NINE-STEP METHOD

MOEs were characterized using a modified application of Langford's nine-step method that allows the MOE development concept to become repeatable, and able to be validated with operational and managerial needs (G. Langford, Determinants of Deterrence Effectiveness 2014, 7-12). A flow diagram of the nine step method is displayed in Figure 13:

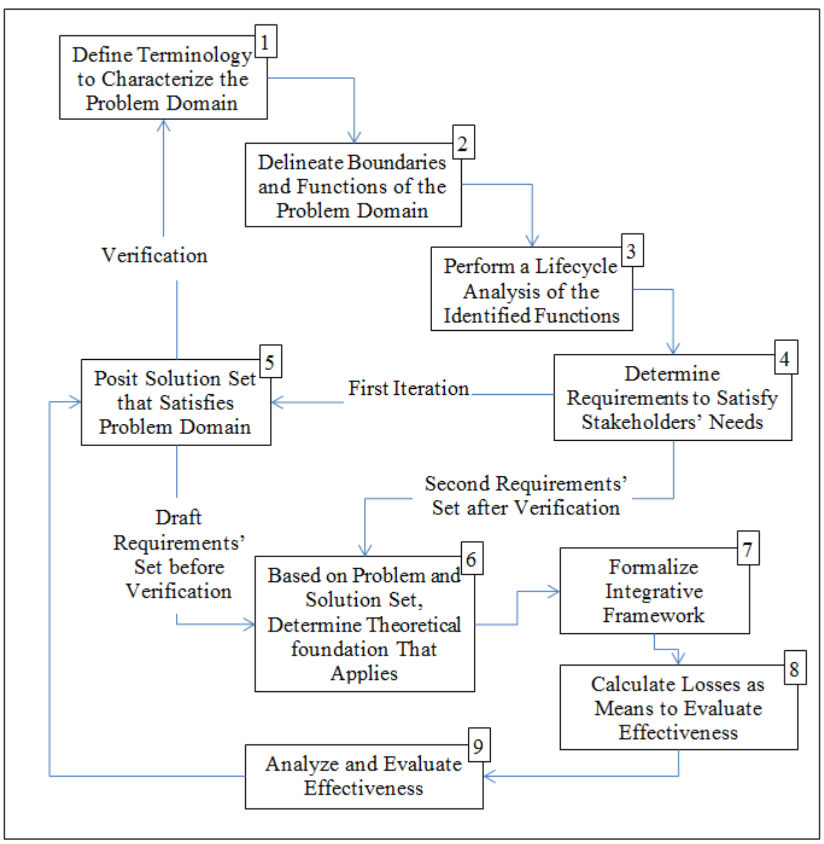

Figure 13. Nine step methodology to characterize MOEs (from G. Langford, Determinants of Deterrence Effectiveness 2014, 12)

This research only used the first seven steps of the nine-step method. The last two steps are better used during MOE reevaluation. The seven steps used in this study and their application to CMMS MOE development are described below (G. Langford, Determinants of Deterrence Effectiveness 2014, 7-12):

- Define terminology: Defined CMMS, CBM+, and other maintenance management working terms to determine the research scope.
- Delineate boundaries and functions: Performed a functional analysis of the key measurable CMMS and management functions.
- Perform lifecycle analysis: Defined the life cycle of the key measurable CMMS and management functions.
- Define requirements: Derived stakeholder requirement by analyzing solicited stakeholder needs.
- Postulate solution set: Developed a set of solutions to satisfy the problem domain issues.
- Determine theoretical foundations: Applied management maintenance and logistics theory to the problem issue.
- Formalize framework: Mapped subjective elements to objective elements using the integrative framework.

1. Define Terminology

A set of selected CMMS MOE terms were defined. The terms were chosen based on their quality to bound and scope the work within the problem (G. Langford, Determinants of Deterrence Effectiveness 2014).

2. Delineate Boundaries and Functions

The key functions of the function 'To Manage' were analyzed and delineated. The functional decomposition facilitated the MOE development by providing specificity to the multiple sub-functions involved in management.

3. Perform Lifecycle Analysis

This section analyzes the lifecycle of a work-order as it relates to maintenance management. The maintenance management lifecycle was derived from the traditional Navy surface maintenance process described in the Joint Fleet Maintenance Manual. This lifecycle analysis clarifies the scope of the problem.

4. Define Requirements

CMMS requirements were derived from stakeholders' CMMS needs. The stakeholders' needs were derived from condition-based maintenance plus (CBM+) policy documents, LCS concept of operations, and supplemented by input from CMMS power users. Department of Defense (DOD) and Navy CBM+ policy documents and instructions provide a set of specified needs and general descriptions of the expected accomplishments and gains resulting from the correct imlpementation of the maintenance approach. CMMS power users included maintenance managers belonging to civilian contractors and government personnel. The power users provided real needs, perceived needs, and expressed needs as they relate to their experience at specific jobs and tasks including supply management, maintenance planning, information technology (IT) analysis, and reliability engineering. Some of the needs provided by users were motivated by the set of realized needs resulting from the current CMMS in use. The overarching set of needs was analyzed, prioritized, and developed into CMMS operational and functional requirements. These requirements were later used for MOE traceability and validation.

5. Postulate Solution Set

A solution set based on the CMMS requirements and problem scoping was proposed.

6. Determine Theoretical Foundations

Applicable theories of social behavior were applied to the situation for CMMS usage. The theories selected as applicable to this problem were management theory and decision theory.

7. Formalize Integrative Framework

The MOE development framework was derived from Langford's integrative framework (G. O. Langford 2012, 81-99). The framework captures the product and management needs in the nexus formed by the intersections of an objective frame and a subjective frame. The intersections of frame elements create nine cardinal points that represent the MOE domains. An MOE set that captures all the necessary objectives required for success shall cover all domains in the framework. Figure 14 displays the framework's

two frames, the domain descriptions, and domain elements. The arrows in Figure 14 indicate the interaction sequence between the product or service in the objective frame and the process in the subjective frame. The sequence begins with cognitive structures, completing a cardinal point before moving to the next. The following is a typical sequence to navigate the framework (G. O. Langford 2012, 88):

- Cognition-Objects, Cognition-Functions, Cognition-Behaviors
- Procedures-Objects, Procedures-Functions, Procedures-Behaviors
- Models-Objects, Models-Functions, Models-Behaviors

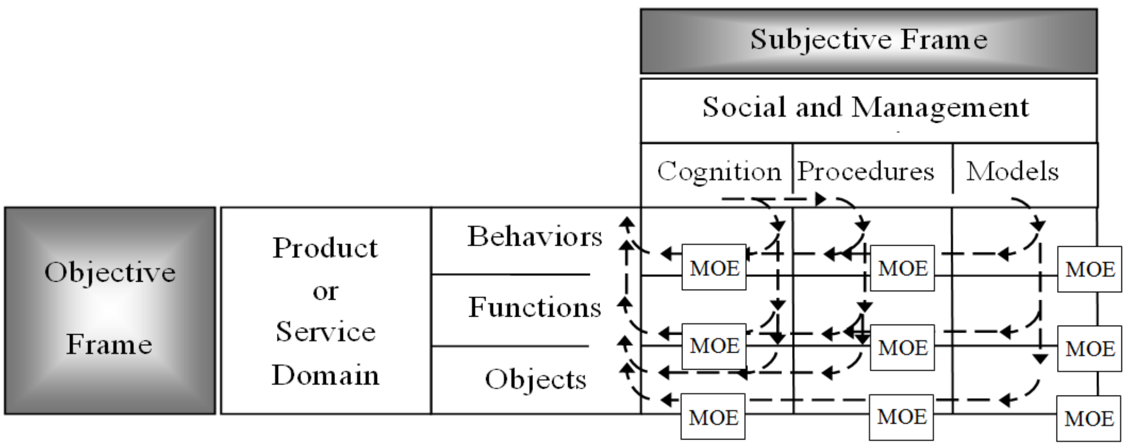

Figure 14. Integrative framework (from G. Langford, Determinants of Deterrence Effectiveness 2014, 7)

Figure 15 displays the framework with descriptions of the domain elements and the cardinal points created at each intersection.

			Integration method		
			Processes		
			Abstractions (and reasoning)	Mechanisms, procedures, activities	Models, representations
OBJECTS	Product*Service	User behaviors (associated with or due to product*service)	Conceptualization pertinent to user behaviors due to product*service	Process and mechanisms describing user behaviors due to product*service	Models or representations of the user behaviors
		Functions (associated with or because of objects that comprise product*service)	Conceptualization delineating uses provided by product*service	Process and mechanisms achieving complete portroyal of product*service functions	Models or representations showing all functions
		Physical entities (associated with or because of objects that comprise product*service)	Identifying and interpreting the product*service physical artifacts, and ascribing meaning	Process and mechanisms resulting in the development of all physical elements	Models or representations of all physical elements

Figure 15. Integrative framework with MOE domain description (from G. O. Langford 2012, 89)

Figure 16 displays the framework with descriptions of the specific MOEs that result from the process object relationships at each cardinal point.

		Processes		
		Cognition	Procedures	Models & Representations
Objects	User Behaviors	Conceptualization of stakeholder behaviors **(MOE-a)** when the product*service is used; and when it not used (or available) **(MOE-p)**	Influence of procedures on processes and mechanisms describing user behaviors due to product*service **(MOE-i)**; Influence describing user behaviors due to lack of product*service **(MOE-f)**	Comparison of expectations of models or representations of stakeholder behaviors to actions **(MOE-t)**; Evaluation of behaviors to predicted actions **(MOE-v)**
	Functions	Prognostication of consequences of interactions between objects through exchange of EMMI **(MOE-g)**; & Expectations of interactions **(MOE-c)**	Availability and Validity of processes and mechanisms that determine resource utilizations for functions **(MOE-u)**; Processes and mechanisms that define the boundary conditions for anticipated operations of all functions **(MOE-b)**	Models/representations showing all functional performances **(MOE-n)**; Models/representations showing all functional performance's quality **(MOE-q)**
	Physical Entities - Object	Experience with posited objects **(MOE-e)** & anticipated responses of posited objects **(MOE-r)**	Availability and Validity of processes and mechanisms resulting in the selection and development of all physical elements **(MOE-s)**; Processes and mechanisms resulting in the development of all physical elements and operational contexts **(MOE-x)**	Models or representations of all physical elements, (structures, properties, traits, and attributes **(MOE-o)**; Models or representations of all social, political, economic elements **(MOE-j)**

Figure 16. MOE Framework Cardinal Points (from G. Langford Building the Determinants of Technology Effectiveness 2014, 12)

The user needs, theoretical foundations, and system and functional requirements were used to map the cognitive and procedure processes to physical objects in the integrative framework to develop the MOEs.

This analysis focused on the lower left 2×2 grid including Cognition-Object, Cognition-Function, Procedure-Object, and Procedure-Function. The 'Models & Represenatations' domain requires to be completed using a specific system and organization to provide the necessary architecture elements for modeling. The purpose of this study is to generate a set of MOEs that is applicable to any maintenance management software. The domain is outside of the scope of this study. A framewok tailored to this study's scope is displayed in Figure17.

		Processes	
		Cognition	Procedures
Objects	Functions	Prognostication of consequences of interactions between objects through exchange of EMMI **(MOE-g)**; & Expectations of interactions **(MOE-c)**	Availability and Validity of processes and mechanisms that determine resource utilizations for functions **(MOE-u)**; Processes and mechanisms that define the boundary conditions for anticipated operations of all functions **(MOE-b)**
	Physical Entities - Object	Experience with posited objects **(MOE-e)** & anticipated responses of posited objects **(MOE-r)**	Availability and Validity of processes and mechanisms resulting in the selection and development of all physical elements **(MOE-s)**; Processes and mechanisms resulting in the development of all physical elements and operational contexts **(MOE-x)**

Figure 17. Modified Integrative Framework (from G. Langford, Building the Determinants of Technology Effectiveness 2014, 12)

Once developed, the MOEs were validated by tracing them to the CMMS user requirements.

V. MEASURES OF EFFECTIVENESS DEVELOPMENT

This chapter follows the development of a set of eight MOEs using the nine step methodology. The MOEs capture the fitness-for-purpose of a CMMS implementation.

A. TERMINOLOGY DEFINITION

CMMS and maintenance terminology was defined in Chapters I, II, and III. A list of selected defined terms that bound the scope of the problem is included in this section.

- Maintenance: The administrative and technical actions required to maintain an item in a condition in which it can perform its intended function (INCOSE 1998, 137). Maintenance needs define the maintenance management approach.
- Reliability centered maintenance (RCM): A logical function-oriented process that identifies optimal equipment maintenance requirements based on reliability characteristics and operating conditions. Its goal is to eliminate PM tasks that do not add value to the maintenance process by using reliability data to adjust maintenance time intervals.
- Preventive maintenance (PM): A time-driven maintenance strategy based on calendar time, equipment operating time, or a number of cycles intended to prevent unscheduled downtime or damage that may lead to a catastrophic failure (Department of Defense 2008, 2-2).
- Condition-based Maintenance Plus (CBM+): An RCM derived maintenance strategy that uses real time or near real time system reliability sensor data, and other RCM methods to determine the best maintenance requirements for a system.
- Corrective maintenance (CM): Reactive maintenance that includes all unscheduled maintenance actions executed as a result of system malfunction, failure, or deterioration (Navy Personnel Command 2013).
- Computerized maintenance management system (CMMS): Fundamental CBM database tools that assists maintenance activities in decision making regarding planning, management, and administration of maintenance actions. The CMMS is an interactive equipment parameter and condition database that can receive data input from users or from sensors and meters. The equipment data is stored as a system-specific maintenance history that may be used by decision makers to detect trends and perform analysis.
- Measures of effectiveness (MOE): A combination of measures intended to determine to what extent objectives are accomplished and how well the

results compare with the desired results (G. Langford, Building the Determinants of Technology Effectiveness 2014, 5).

B. MAINTENANCE MANAGEMENT FUNCTIONS DELINEATION

The functions of maintenance management are:

- To plan
- To communicate
- To organize
- To direct
- To control

Maintenance managers employ these functions via the CMMS program to create synergy amongst the maintenance team members including contract specialists, planners, maintainers, and other managers. Figure 18 displays the functional hierarchy of the function: "To Manage Maintenance".

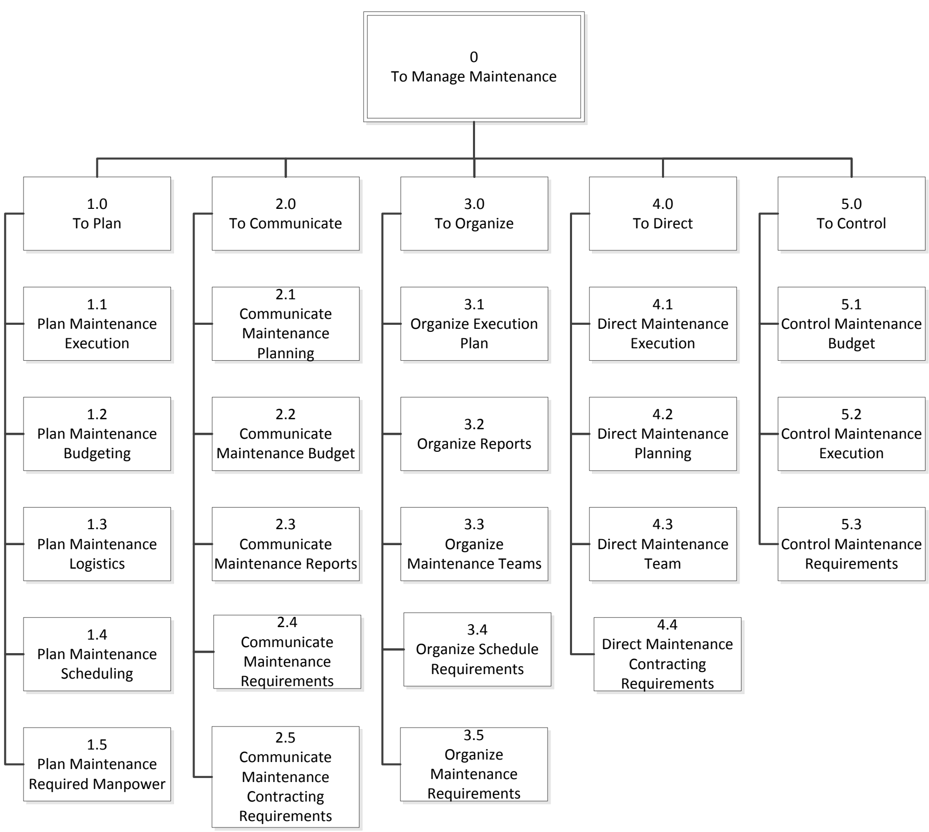

Figure 18. Maintenance management functional hierarchy

1. To Plan

The function 'to plan' includes the available CMMS activities required to conduct necessary maintenance planning. Traditionally, the planning function is fundamental to any CMMS program because it predicts and helps organize the required data used in its modules.

a. Plan Maintenance Execution

Maintenance execution planning includes planning the required equipment maintenance actions and repairs. Maintenance execution planning considers the availability of the correct tooling, parts, personnel, maintenance authorizations, and coordination within maintenance activities.

The CMMS should provide execution planning information in the work-order data and the logistics and scheduling modules.

b. Plan Maintenance Budgeting

Maintenance budgeting planning includes calculating and estimating the required funds for upcoming maintenance. The CMMS provides a list of upcoming required maintenance data that includes required parts, estimated duration of repair, personnel requirements, and equipment nomenclature.

c. Plan Maintenance Logistics

Maintenance logistics planning includes estimating the required parts and consumables supply and all shipping and transportation planning for maintenance.

d. Plan Maintenance Scheduling

Maintenance scheduling planning includes the planning and coordination of the maintenance availability scheduling considering supply and parts delivery times, foreseen delays, and integrated work planning.

e. Plan Maintenance Required Personnel

Maintenance personnel requirement planning includes the planning and coordination of available maintenance personnel to complete the required maintenance within schedule.

2. To Communicate

The function 'to communicate' includes the available CMMS activities required for transferring maintenance management information within and outside of the organization. All entities involved in the maintenance management efforts share a common picture when the CMMS' communicating function is employed effectively. Managerial situational commonality is fundamental for swift and effective decision making.

a. Communicate Maintenance Planning

Maintenance planning communications include the transfer of all information required to create a common situational picture to facilitate planning.

b. Communicate Maintenance Budget

Maintenance budget communications include the transfer of all budgetary information required to create a common situational picture to facilitate maintenance management.

c. Communicate Maintenance Reports

Maintenance report communications include the transfer of all reports available to the maintenance management teams providing the required maintenance information to direct and manage resources. Typical maintenance reports may include but are not limited to progress, logistical, equipment status, and budgetary information.

d. Communicate Maintenance Requirements

Maintenance requirements communications include the transfer of all information involving established maintenance standards and procedures approved by Technical Authority.

e. Communicate Maintenance Contracting Requirements

Maintenance contracting requirements communications includes the transfer of all contracts related information. Effective contracting requirements communication should facilitate the process of placing new and emergent required work on contract for execution.

3. To Organize

The function 'to organize' includes the available CMMS activities that provide structure and order to maintenance management information. Effective organization provides a common structuring system to the data available in the program.

a. Organize Execution Plan

Execution planning organization includes the orchestration of maintenance activities to provide an integrated execution plan that reduces delays and work conflict.

b. Organize Reports

Reports organization includes managing the systematic generation of all maintenance management reports.

c. Organize Maintenance Teams

Maintenance team organization includes the orchestration of maintenance teams and other available personnel to properly execute an integrated execution plan.

d. Organize Schedule Requirements

Schedule requirements organization includes the effective generation and upkeep of an integrated work schedule that allows for all required work to be executed sequentially and on time with minimal delays and work conflict.

e. Organize Maintenance Requirements

Maintenance requirements organization includes maintaining the current and established maintenance requirements, standards, and guidance database to ensure all executed work meets the necessary quality assurance requirements.

4. To Direct

The function 'to direct' includes the available CMMS activities that enable the direction of action required in maintenance management.

a. Direct Maintenance Execution

Maintenance execution direction includes the authorization to perform work in accordance with plans, contracts, and schedules.

b. Direct Maintenance Planning

Maintenance planning direction includes the authorization of maintenance activities to plan all maintenance that shall be performed in a specified period.

c. Direct Maintenance Team

Maintenance team direction includes maintenance activities authorizations to perform assigned work in accordance with plans and schedules.

d. Direct Maintenance Contracting Requirements

Maintenance contracts direction includes directing the contractual authorizations required by maintenance activities to perform work in accordance with plans and schedules.

5. To Control

The function 'to control' includes the available CMMS activities that allow managers to exert control and manage certain finite aspects of maintenance.

a. Control Maintenance Budget

Budget maintenance control allows the managers to properly fund work-orders while staying within the budgetary limits and constraints.

b. Control Maintenance Execution

Maintenance execution control allows the managers to properly direct work execution in accordance with schedule and contractual limits and constraints.

c. Control Maintenance Requirements

Maintenance requirements control allows the managers to properly execute work in accordance with approved maintenance requirements and standards.

C. MAINTENANCE MANAGEMENT FUNCTIONAL CYCLE ANALYSIS

The work-order lifecycle, from the maintenance manager's viewpoint, consists of four stages: validation, planning, execution, and closeout. Each stage contains several CMMS maintenance management functions; some functions remain relevant throughout several stages.

The first stage is work-candidate validation, screening, and brokering. During this stage the maintenance managers review the work-candidates and validate them to determine the request's reasonability. Work-candidate reasonability is primarily determined by the equipment's degradation impact on the ship's mission. Once the work candidate is validated, the manager screens it by determining the specific maintenance execution period and brokers it by selecting the maintenance activity that will execute the work. This stage requires the functional elements used for preliminary planning, schedule and maintenance requirements, and communication.

The second stage is work-order planning. During this stage the maintenance manager and maintenance teams determine the correct technical specifications, cost estimates, overall planning, and best practices and approach for the specific work-orders. The work-order planning stage employs most of the CMMS functional elements and involves the integrated coordination of the maintenance team.

The third stage is work execution. All the planned work is executed during this stage in accordance with the work-orders and conforming technical authority. Additionally, any new work or growth work that arises during execution begins the cycle at the first stage. The execution stage employs all of the CMMS functional elements as it involves steps from every stage of the maintenance management functional cycle.

The fourth stage is work closeout. During work closeout all the maintenance activities input the final work-order information and report the work status. If neglected, the lack of closeout work-order information in the CMMS hampers the CBM+ approach. CBM+ relies on up-to-date equipment status and performance data to determine trends and conduct RCM analysis.

The four principal work-order lifecycle stages and their corresponding maintenance management functions are summarized in Table 3.

Table 3. Work-order management lifecycle functional allocation

Work Candidate Validation, Screening, and Brokering	Work Order Planning	Work Order Execution	Work Order Closeout
<u>To Plan</u> - Budgeting - Logistics - Scheduling - Manpower requirements	<u>To Plan</u> - Execution - Budgeting - Logistics - Scheduling - Manpower requirements	<u>To Plan</u> - Execution - Budgeting - Logistics - Scheduling - Manpower requirements	<u>To Plan</u> - Scheduling
<u>To Communicate</u> - Planning - Budget - Reports - Maintenance requirements - Contracting requirements	<u>To Communicate</u> - Planning - Budget - Reports - Maintenance requirements - Contracting requirements	<u>To Communicate</u> - Planning - Budget - Reports - Maintenance requirements - Contracting requirements	<u>To Communicate</u> - Budget - Reports - Maintenance requirements - Contracting requirements
<u>To Organize</u> - Reports - Schedule requirements - Maintenance requirements	<u>To Organize</u> - Execution Plan - Reports - Maintenance teams - Schedule requirements - Maintenance requirements	<u>To Organize</u> - Execution Plan - Reports - Maintenance teams - Schedule requirements - Maintenance requirements	<u>To Organize</u> - Reports - Maintenance requirements
<u>To Direct</u> - Maintenance team	<u>To Direct</u> - Planning - Maintenance team - Contracting requirements	<u>To Direct</u> - Execution - Planning - Maintenance team - Contracting requirements	<u>To Direct</u> - Maintenance team - Contracting requirements
<u>To Control</u> - Requirements	<u>To Control</u> - Budget - Requirements	<u>To Control</u> - Budget - Execution - Requirements	<u>To Control</u> - Budget - Execution - Requirements

D. CMMS REQUIREMENTS DEFINITION

The requirements definition process' purpose "is to define the requirements for a system that can provide the services needed by users and other stakeholders in a defined environment" (International Organization for Standardization, and International Electrotechnical Commission 2008, 36). The CMMS needs are derived from conversations

with CMMS users, maintenance management stakeholders, and DOD and NAVSEA source documents. These needs frame the MOE development process.

1. Stakeholders' Needs

A stakeholders' CMMS needs summary is displayed below in table 4. The categories grouping the needs are related to the aspect of the system addressing the individual needs.

Table 4. Stakeholder need summary

Interface Needs	Data Generation Needs	Management
Provide a simple interface to update work-order data	Generate work-orders list	Track progress and deferred work-orders
Allow the user to record as much work-order data as possible	Generate a work schedule	Allow for availability planning and scheduling (IMS)
Provide dashboards with built in analysis, reasoning, and decision support that minimizes user interaction	Provide maintenance data in support of reliability, maintainability, and sustainability analysis	Facilitate coordination and sharing of data
Be scalable to different classes of hardware and software platforms including Navy maintenance legacy programs.	Process and display, as part of a prognostic or diagnostic evaluation, the equipment and system health to the crew	Avoid recurring cost licensing
Be operable with different classes of hardware and software platforms	Collect meter data	Reduce planning time
Be customizable to the user	Display equipment performance trends	Increase planning accuracy
Provide a back door for flexible customization by IT personnel	Allow extraction of ad hoc reports	Reduce data entry errors
Conform to all applicable Navy and DOD IT policies and requirements	Provide automated sustainment info and metrics	Reduce time delays to process work authorization and planning
Have a web browser based UI to allow off ship support to view the same maintenance info as onboard the ship	Provide equipment data that may be transmitted for notification, analysis, and archival purposes	Optimize TOC
	Provide accurate supply data	
	Provide risk predictions	

The hierarchical tree in Figure 19 expands on the three categories in the stakeholder need summary displayed above in Table 4.

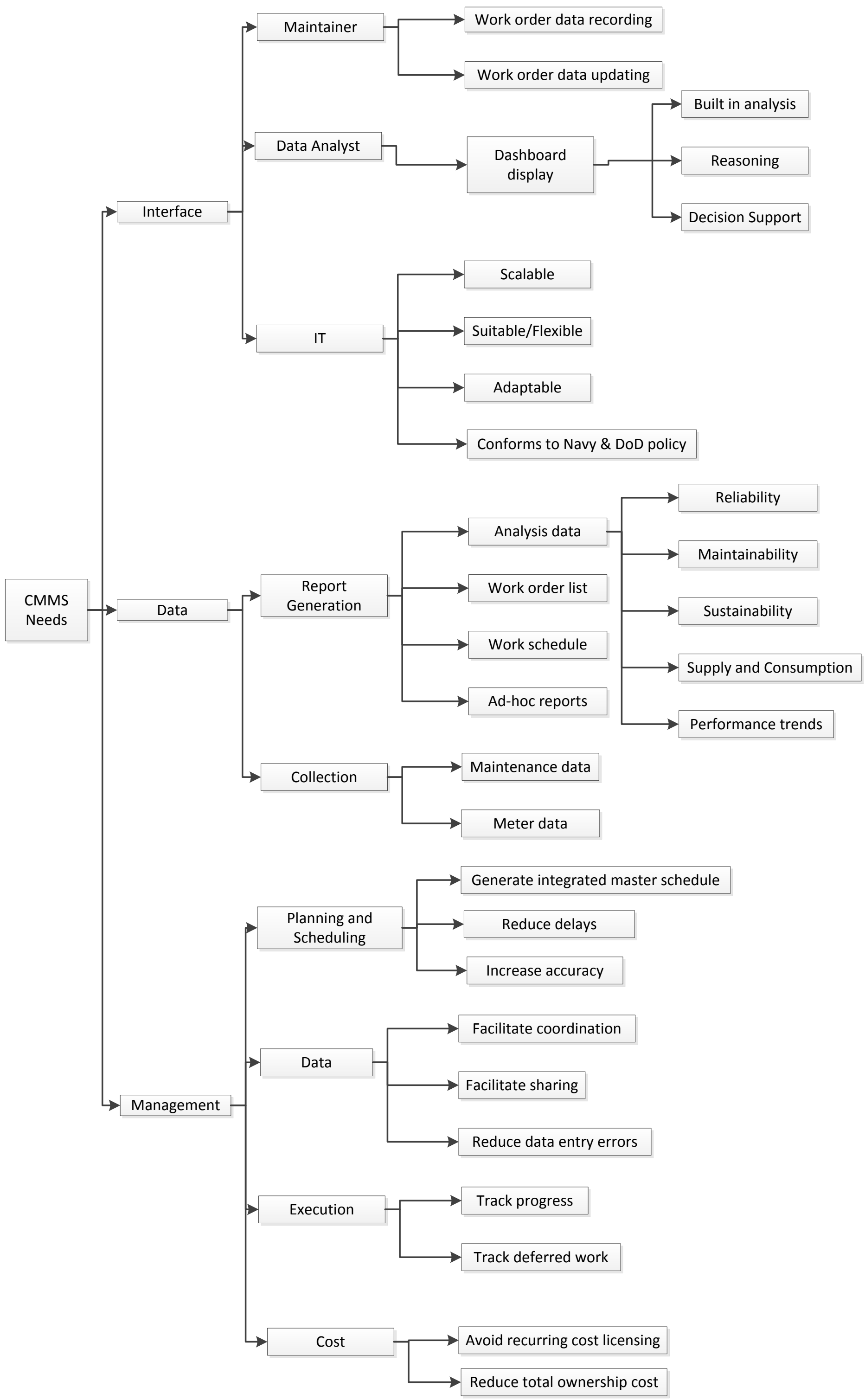

Figure 19. CMMS needs hierarchical breakdown

2. CMMS Constraints Definitions

The CMMS requirements are bounded by constraints imposed on the system. The constraints included in this analysis are derived from the limitations encountered by the LCS program.

CMMS communication functionality is constrained by unreliable ship-to-shore CBM data transmission (United States Government Accountability Office 2013). The shipboard broadband communication capabilities limit the ability to transmit CBM+ data. Real-time or near-real-time equipment data is fundamental for the successful implementation of a CBM+ program. Currently, the majority of the equipment data is inputed manually by maintainers while executing work-orders because Navy ships are not designed with the sensors and meters required for CBM+ data recording automatization.

The COTS CMMS program currently used for maintenance management does not interface with all Navy maintenance management legacy programs. This constraint prevents the development of a common maintenance picture and results in the use of ad-hoc reporting.

3. CMMS Requirements

The following requirements are derived from the stakeholders' CMMS needs.

- The CMMS shall provide the user the ability to record and update all critical, descriptive, maintenance data on a work-order as required by the specific equipment.
- The CMMS shall display a customizable dashboard that provides decision makers with all the required necessary information to conduct maintenance management and other related tasks.
- The CMMS shall be scalable to different classes of hardware and software platforms.
- The CMMS shall be operable with different classes of hardware and software platforms.
- The CMMS shall be customizable.
- The CMMS shall possess a web browser user interface that provides the user with the most up-to-date maintenance data.

- The CMMS shall generate reports to facilitate analysis of equipment reliability, maintainability, sustainability, consumption, and performance as required to support maintenance management.
- The CMMS shall generate a work-order list by user modified query.
- The CMMS shall generate an accurate integrated work-order execution schedule.
- The CMMS shall record and maintain equipment maintenance data.
- The CMMS shall provide all users a common maintenance status.
- The CMMS shall allow users to coordinate and share maintenance requirements.
- The CMMS shall maintain work execution status.
- The CMMS should not require periodic licensing.

E. POSITED SOLUTION SET

The CBM+ approach requires a CMMS that satisfies the stakeholder requirements in order to facilitate maintenance management. As the aim of this study is to develop a set of MOEs applicable to any CMMS, it is assumed that the selected CMMS can potentially satisfy all stakeholder requirements if used correctly and effectively. This assumption provides a basis for logical reasoning.

A satisfactory CMMS is one that aids decision makers to manage maintenance by providing the functions to forecast, plan, communicate, and record maintenance history as required.

F. THEORETICAL FOUNDATIONS

The successful employment of the posited solution set is rooted in management theory, organization theory, and decision theory. These theories are a foundation to the understanding of management and decision making dynamics.

1. Management Theory

Management is defined as “designing, providing, and maintaining a conducive internal environment in tune with the opportunities and challenges of the external environment through planning, organising, directing, and controlling all resources and

operations in order to achieve effective organisational strategies efficiently" (Rao 2010, 3). The theory explains management as a discipline composed by sets of functions, roles, skills, and functional areas derived through management thought (Rao 2010, 3-16).

Management theory provides the functional capabilities discussed earlier in this chapter (see Figure 18). The theory also delineates the different management team member roles and skills required for effective management.

2. Decision Theory

Decision theory explains "how individuals or groups make or should make decisions" (Resnik 1987, 3). A ship maintenance management decision maker expects the CMMS to provide reliable equipment data to determine the maintenance requirements based on forecasting and planning. Decision theory explains how an individual should make a decision involving "two or more options or acts, each of will produce one of several outcomes" (Resnik 1987, 6). For example, a maintenance manager might face the choice of deciding whether to execute or defer maintenance based on equipment trends and reliability requirements. The decision of maintenance execution has several possible outcomes such as: defer and the equipment does not fail, defer and the equipment fails, execute early and potentially wasting funding on unnecessary maintenance, execute maintenance on time. Each of these outcomes has a set of consequences that affect the decision maker's thought process.

Probability theory and utility theory expand the aspects of the decision theory that explain how individuals or groups make decisions based on sets of known probabilities and conditions of different states of a problem. Utility theory explains how individuals or groups make decisions in order to maximize their utility. Luce and Raiffa (1957, 15) describe utility theory-based decision making as: "Given a set of possible acts, to choose one (or all) of those which maximize (or minimize) some given index". Measurable utility is specific to the organization conducting the maintenance management. Ship maintenance traditionally seeks to maximize reliability and availability while minimizing maintenance costs and equipment downtime. There are more measurable maintenance utility categories but traditionally cost, reliability, and availability are the two that lie at a maintenance organization's heart.

G. INTEGRATIVE FRAMEWORK FORMALIZATION

The integrative framework has nine cardinal points created by the intersection of the problem's subjective and objective domains. This research includes MOEs developed to fulfill the intersections of the process domain's 'Cognitive' and 'Procedures' columns with the object domain's "Object" and "Function" rows.

1. Cognitive Domain

The cognitive domain captures the abstractions and reasoning that arise with the CMMS as a management product and service. The domain addresses the following relationships cognition-object, cognition-functions, and cognition-behavior.

a. Cognition-Object

The cognition-object cardinal point seeks to identify, interpret, and ascribe meaning to the object that provides the service (G. O. Langford 2012, 89). The object is the CMMS program. The MOEs developed in this cardinal point relate to the user's experiences with the CMMS technology; it specifically addresses the consequences of using the CMMS and the program's anticipated responses (G. Langford, Determinants of Deterrence Effectiveness 2014, 23).

The cognition-object cardinal point takes into account all functional aspects of the CMMS. Some questions that arise in determining the evaluation factors for the cognition-object cardinal point are (G. O. Langford 2012, 90-91):

- How does the user operate the CMMS?
- What decisions are made because of the CMMS?
- How is the CMMS organized for use?
- How is the CMMS operated?
- What type of feedback does the CMMS provide the user?
- How does the CMMS communicate with other objects?

(1) MOE-e: CMMS Experience

CMMS users may execute actions related to the five maintenance management functions: planning, organizing, controlling, directing, and communicating. If the CMMS'

purpose is to assist maintenance activities in decision making regarding planning, management, and administration of maintenance actions, then the effectiveness of the system as it relates to the user's experience indicates how well the users utilize the system's available capabilities to perform each of the maintenance functions.

The CMMS capability employment may be measured by determining the percentage of work-orders that require typical management tasks to happen outside of the CMMS. To capture this information, the CMMS IT group could embed a task breakdown checklist within the work-order for the user to indicate which typical steps related to that task at hand are being performed outside of the system. The items on the task breakdown checklist would only include those steps that are expected to happen within the system. For example, in order to build an accurate maintenance history it is important that tasks such as 'Indicate maintenance completion' or 'Provide reason for work deferral' be completed and captured in the system. However, a common administrative task like contract negotiation should not be expected to take place within the CMMS. Although the information and cost data resulting from the negotiations belong in the database, it might be unreasonable to expect a government contracting officer representative and a contractor to conduct cost negotiations via the CMMS.

The CMMS experience MOE (MOE-e) provides insight into the effectiveness of system usage as it relates to recording, updating, coordination, and communication of maintenance data.

$$\text{MOE-e} = \frac{\text{\# Task Elements Completed Using CMMS}}{\text{\# Available Task Elements Expected to be Completed Using CMMS}}$$

(2) MOE-r: CMMS Response

The CMMS' response to the user and other objects is a system characteristic that expands through all five maintenance management functions. CMMS effectiveness as it relates to the system's response indicates how well the system interacts with other systems and the users. System feedback through the user interface provides an alert describing the success status of an executed action within the system. A user's action success status alert

may indicate the accuracy and completeness of the equipment data that is being inputted into the system.

Satisfactory CMMS responsiveness may be measured by determining the percentage of work-orders requiring additional reviews as a result of incorrect or incomplete work-order data. To capture this information, the maintenance management team should capture any instances of administrative work-order rework. Any type of rework resulting from bad or incomplete data could be considered a missed opportunity for the CMMS to provide feedback by alerting the user of the error.

The CMMS response MOE (MOE-r) provides insight into the effectiveness of the management and reporting of maintenance data and the system's interface with objects.

$$\text{MOE-r} = \frac{\text{\# Work Orders Requiring Administrative Rework}}{\text{\#Work Orders}}$$

b. Cognition-Function

The cognition-function cardinal point seeks to identify, interpret, and ascribe meaning to the CMMS program's functions (G. O. Langford 2012, 89). The MOEs developed in this cardinal point relate to the predictions and expectations of events resulting from the system's exchange of energy, matter, material wealth, and information (EMMI) (G. Langford, Determinants of Deterrence Effectiveness 2014, 23). The principal focus of this MOE development analysis is on the 'information' element of EMMI exchange.

The cognition-function cardinal point involves the reasoning of the CMMS' functional aspects. Some questions that arise in determining the cognition-function cardinal point evaluation factors are (G. O. Langford 2012, 90-91):

- How will the user enable and use the CMMS functions?
- What processes are necessary to assist the user to make full use of the CMMS?
- How is the CMMS organized by functions?
- How does the CMMS functional organization impact user behavior?
- How are functions sequenced in the CMMS for the various maintenance roles?

- Are the CMMS functions being performed properly?

(1) MOE-g: CMMS Functionality Prediction

The CMMS serves its purpose as a maintenance management tool only when it exchanges data with an object. The ‘object’ exchanging data with the CMMS in a CBM+ approach could be a meter or sensor installed on monitored equipment or the user. The CMMS functionality prediction provides an object-system information exchange consequence indication. CMMS effectiveness as related to the system’s functionality prediction can be linked to how well it provides the user with the expected tools to complete the maintenance management tasks for which they are responsible. For a CMMS program to be considered fit-for-purpose it shall provide all users the required capabilities and functionalities to be able to properly manage a work-order in accordance with regulations.

Functionality prediction may be measured by periodic evaluation of the CMMS. These evaluations should be completed by CMMS trained users who perform tasks requiring data input or review of the data that has been entered into the system. The evaluation shall be customized for the user-evaluator to include categories applicable only to the evaluator’s area of responsibility within the maintenance management cycle. The functionality categories include the necessary processes to complete maintenance tasks and system organization. Users can evaluate the system on how well it follows the maintenance process once information has been entered. For example, if a sensor indicates a reduction in oil flow in a main reduction gear nozzle, a user should predict the receipt of an alert when the CMMS receives the oil flow data from the sensor. A different example could be a maintainer’s prediction that after entering a new work-order request in the system it will alert the port engineer for revision and approval. In both of these cases the users prognosticate the CMMS’ function predictability. A predictable system enables all users to trust the system.

Once the user scores are compiled, they shall be weighed and normalized. The resulting ‘CMMS functionality score’ provides an estimate of how well the program performs the predicted traditional steps required for a user to complete their maintenance related tasks while meeting their expectation as it relates to CMMS functionality. CMMS expectations should be formed and evaluated by users with CMMS training. These users will

understand the attainable functionality of the system and how it differs from other maintenance databases and programs.

The CMMS functionality expectation MOE (MOE-g) provides insight into the effectiveness of the predicted functional results arising from interactions between the systems and data reporting objects.

$$\text{MOE-g} = F.C._1 \times W_1 + F.C._2 \times W_2 \ldots + F.C._n \times W_n = \sum_{i=1}^{n} F.C._i W_i$$

Where $F.C._i = F.C._1, F.C._2, \ldots F.C._n$ are the functionality category scores assigned during the evaluation and $W_i = W_1, W_2, \ldots W_n$ are the weights associated with each category. The category weights may be assigned using a multiple criteria analysis weighing process.

(2) MOE-c: CMMS Functionality Expectation

The CMMS functionality expectation MOE provides a measurement of the users' perceived system fitness-for-purpose based on how well the CMMS meets the expected results. Result expectations are based on the user's desired system functional requirements. For a CMMS program to be effective it shall provide users a set of expected results and capabilities once the maintenance data has been entered.

This MOE is measured with the same method used to calculate MOE-g, functionality prediction. This method requires a periodic evaluation of the CMMS functionality by selected users. Users can evaluate the system on how well its functionality and their expectations in accomplishing maintenance tasks match. For example, a maintenance manager who is planning the work package for upcoming maintenance availabilities should expect the CMMS to generate a preliminary list of potential work-orders based on equipment maintenance history. If the CMMS does not generate the work-order candidate list then the user's expectations are not met and the system's functionality expectations are evaluated accordingly. Another possibility is that the program only generates a list of scheduled or overdue preventive maintenance work-orders but fails to recommend new work-orders based on equipment condition assessments and findings. If the maintenance manager's expectation is that a satisfactory CMMS should automatically recommend work based on condition

assessments then the evaluation should result in a MOE that indicates partial meeting of needs and an opportunity to improve the system's functionality.

The CMMS functionality expectation MOE (MOE-c) identifies user satisfaction based on system expectations. A low score could potentially indicate an opportunity for system or process improvement.

$$\text{MOE-c} = F.C.E._1 \times W_1 + F.C.E._2 \times W_2 \ldots + F.C.E._n \times W_n = \sum_{i=1}^{n} F.C.E._i W_i$$

where $F.C.E._i = F.C.E._1, F.C.E._2, \ldots F.C.E._n$ are the expectation score assigned during the evaluation for the specific functionality category and $W_i = W_1, W_2, \ldots W_n$ are the weights associated with each category.

c. Cognition-User

The cognition-user cardinal point seeks to identify, interpret, and ascribe meaning to the CMMS program's user behaviors when the program is in use and when it is not available or in use (G. Langford, Determinants of Deterrence Effectiveness 2014, 23).

The cognition-user cardinal point involves the reasoning of the CMMS user's behaviors before the program is used, during its use, and after its use and their anticipation when it is not in use (G. O. Langford 2012, 90). Some questions that arise in determining the cognition-user cardinal point evaluation factors are (G. O. Langford 2012, 90–91):

- What should the users anticipate when the CMMS is in use?
- What should the users anticipate when the CMMS is unavailable?
- What should the users anticipate when the CMMS is not in use?
- How do users organize their work with and without the CMMS?
- How are the users' behaviors changed to complete the maintenance management tasks based on the CMMS limitations?

Cognition-user MOEs are not developed in this research. These MOEs are better developed once a CMMS has been selected and implemented and is being operated by all the maintenance management users. The organization members determined to be users will shape this cardinal point.

2. Procedural Domain

The procedural domain captures the procedures and mechanisms of the CMMS as a management product and service. The domain addresses the following relationships procedure-object, procedure -functions, and procedure -behavior.

a. Procedure-Object

The procedure-object cardinal point seeks to identify the validity of the CMMS selection and development of CMMS procedures (G. Langford, Building the Determinants of Technology Effectiveness 2014, 12). The MOEs developed in this cardinal point relate to the effectiveness of the specific CMMS selection and to how the technical aspects of the system's processes meet the stakeholder's needs (G. Langford, Determinants of Deterrence Effectiveness 2014, 23).

The procedure-object cardinal point focuses on the processes and mechanisms related to the CMMS. Some questions that arise in determining the evaluation factors for the procedure-object cardinal point are (G. O. Langford 2012, 91):

- Do the CMMS procedures reflect the maintenance desired outcome?
- Do the CMMS procedures reflect the project requirements?
- Are the CMMS procedures driving the maintenance management towards the desired outcome?
- Does the CMMS operate as desired while interacting with external influences?
- Does the CMMS clearly differ from other competitive products?

(1) MOE-s: CMMS Selection Validity

In a CBM+ environment the CMMS is not effective as a standalone system. The information exchange between the CMMS and the data providers determines the system's fitness-for-purpose. The CMMS' goal in a CBM+ management approach is to provide the necessary tools for the maintenance managers to execute their tasks and make decisions with the greatest amount of near real-time data. Evaluating the CMMS' validity should provide indications of the program's suitableness to help meet the overarching maintenance

organization's goals of reduced maintenance costs and increased equipment life expectancy and availability.

There are many capable and competitive CMMS and EAM COTS products that may be selected by a maintenance organization. The 'CMMS selection validity' MOE (MOE-s) evaluates the effectiveness of the current CMMS' selection as it relates to organizational goals. The validity of a selected CMMS may be measured by the periodic evaluation of the system as an object. This evaluation should be performed by high level managers and power users because its foci are bounded by high level organizational goals. The evaluators shall score the system on how well it serves as a tool in reducing lifecycle costs and increasing equipment availability.

The CMMS selection validity MOE identifies the high level stakeholder's satisfaction with the selected CMMS based on programmatic goals. A low score could potentially indicate that the CMMS, as an object, lacks the necessary tools to enable the attainment of the programmatic goals. System factor categories are determined by the organization's stakeholders and may include categories such as overall availability, cost control, and meeting expected equipment operational life.

$$\text{MOE-s} = S.F._1 \times W_1 + S.F._2 \times W_2 ... + S.F._n \times W_n = \sum_{i=1}^{n} S.F._i W_i$$

Where $S.F._i = S.F._1, S.F._{2,...} S.F._n$ are the system factor scores assigned during the evaluation for the specific system factor category and $W_i = W_1, W_{2,...} W_n$ are the weights associated with each category.

(2) MOE-x: CMMS Operational Context Validity

The CMMS' operation is influenced by external objects. Some objects that influence the CMMS are users, hardware, and other peripheral equipment and software. The CMMS' ability to interact with external objects determines its scalability, flexibility, and adaptability. A suitable CMMS should require minimal effort to accomplish interaction with different external systems. Evaluating the CMMS' operational context validity should provide indications of the program's ability to work with different types of hardware and software.

The maintenance organization benefits from a scalable, flexible, and adaptable CMMS because its operation can potentially be expanded to new platforms such as handhelds or other organization's software.

The proper measurement of any software's scalability, flexibility, and adaptability requires a set of software engineering skills and knowledge not traditionally found at a Navy Program Office or maintenance organization. For this reason, the calculation of the 'CMMS operational context validity' MOE (MOE-x) only requires input that can be provided by the CMMS power users. Although the CMMS power users and maintenance managers may not know how to measure a program's scalability, flexibility, and adaptability they should be able to recognize successful and unsuccessful opportunities when the CMMS tries to interact with other systems. The validity of the CMMS' operational context may be measured by combining the percentage of systems that successfully interact with the CMMS and the periodic evaluation of the system's interactions with external objects and environments. This evaluation should be performed by the CMMS power users and IT personnel with input from users and maintenance managers.

MOE-x identifies the CMMS' ability to interact with external objects. A low score could potentially indicate limitations in the CMMS' capabilities to communicate and interact with other systems. A lack of communication and interaction between systems results in a situation that requires ad-hoc actions that waste time and resources. Operational context factors are determined by the power users and organization's stakeholders and includes categories that capture the evaluator's perceived system's ability to interact with other systems. The perception will be mostly based on the user's operational experience with the CMMS.

$$\text{MOE-x} = \frac{\#\text{ Systems CMMS Interacts With}}{\#\text{ Maintenance Management Systems Available}} \times Ws + O.C._1 \times W_1 + O.C._2 \times W_2 \ldots + O.C._n \times W_n$$

$$\text{MOE-x} = \frac{\#\text{ Systems CMMS Interacts With}}{\#\text{ Maintenance Management Systems Available}} \times Ws + \sum_{i=1}^{n} O.C._i W_i$$

Where $O.C._i = O.C._1, O.C._2, \ldots O.C._n$ are the system operational context factor scores assigned during the evaluation for the specific category and $W_i = W_1, W_2, \ldots W_n$ are the weights

associated with each category. W_S is the weight assigned to the percentage of systems that are able to successfully interact with the CMMS.

b. Procedure-Function

The procedure-function cardinal point seeks to define and identify the validity of the CMMS resource selection and the development of procedures (G. Langford, Building the Determinants of Technology Effectiveness 2014, 12). The MOEs developed in this cardinal point relate to the CMMS functions' representative mechanisms (G. O. Langford 2012, 89). The functions' mechanisms and procedures effectiveness may indicate how well they fit the stakeholders' organizational, managerial, and maintenance goals. Effective procedures and mechanisms result in less waste for the organization. An effective CMMS operates with functions that support these procedures.

Some questions that arise in determining the evaluation factors for the procedure-function cardinal point are (G. O. Langford 2012, 91):

- Are the CMMS functions constraining resources by duplicating efforts?
- Do the CMMS functions help achieve and support good administrative practices that take into account role assignments and responsibility assignments?
- Do the CMMS functions reflect desired enterprise metrics and project specifics?
- Do the CMMS functions interact with objects outside its boundaries as required to accomplish the management tasks?

(1) MOE-u: CMMS Functional Resource Utilization Validity

Each function performed by the CMMS draws from a finite resource pool. These resources may be monetary, of intellectual capital, or personnel related. The maintenance organization depends on the effective management of these resources to successfully accomplish their mission. If the CMMS' functions and organization results in duplication of efforts then it creates waste in the form of time, motion, and possible talent underutilization. A suitable CMMS should have functions that support good administrative practices that minimize any type of waste.

Effective resource utilization is fundamental to successful management. Navy surface maintenance management resources are additionally constrained by the fiscal environment. A CMMS that cannot support effective resource management will likely fail to meet the overarching CBM+ organizational need to reduce total ownership cost. Organizational resources like intellectual capital may be linked to performance drivers (Alcaniz, Gomez-Bezares and Roslender 2011). If performance drivers are linked to resource management then the effective administration of these resources enables the organization's maintenance managers to create value (Harazin and Pádár 2013, 38). The 'CMMS functional resource utilization validity' MOE (MOE-u) evaluates the system's functions capacity to support effective resource management.

Periodic project or group performance evaluations could provide insight into the efficiency of the CMMS' functions to support resource management. If effective resource management is linked to performance indicators then the performance indicators should point out opportunities to improve aspect of the CMMS functions that do not utilize the available organizational resources efficiently. A periodic evaluation of the system by CMMS users using a balanced scorecard allows them to assign scores to the system's functions as they relate to the processes individual to their task. It is important that the system evaluators understand all the individual tasks that are performed throughout the typical CMMS work-order process. Completing a value stream map helps users understand the full process and facilitates the ability to recognize steps and functions that create waste.

MOE-u provides a metric that captures the system's aggregate functional resource utilization score. A low MOE score indicates opportunities for process improvement by addressing the system's functions. However, it is not necessary to wait for an overall low MOE-u score to identify opportunities to improve the process as they relate to the system's functions. The organization may take action on any of the average individual functional balanced scorecard categories.

$$\text{MOE-u} = F.S._1 \times W_1 + F.S._2 \times W_2 ... + F.S._n \times W_n = \sum_{i=1}^{n} F.S._i W_i$$

Where $F.S._{i} = F.S._{1}, F.S._{2}, \ldots F.S._{n}$ are the average individual functional balanced scorecard scores and $W_{i} = W_{1}, W_{2}, \ldots W_{n}$ are the weights associated with each category.

(2) MOE-b: CMMS Functional Boundary Conditions

Traditional CMMS programs interact with other objects through the system's functions. These objects may be users, other systems, and peripherals. A boundary condition is the "mediation of capabilities that enact across boundaries" between two objects (G. O. Langford 2012, 43). These conditions seek to describe the interactions between objects that exist within their respective boundaries (G. O. Langford 2012, 43). A suitable CMMS' functions should flawlessly interact with other objects and systems to accomplish maintenance management tasks.

The boundary conditions between a CMMS' functions and other objects dictate how well the systems' operation fits its intended purpose. Effective boundary conditions enable the transfer of EMMI, specifically energy and information, between systems. Functional boundary condition effectiveness may be described by characteristics including user interaction, and the CMMS' ability to transfer data between systems without ad-hoc data exchange methods.

MOE-b provides a metric of the CMMS' function's ability to interact with external objects. This MOE may help identify limitations in the CMMS' functions' capabilities to communicate and interact with other objects. The CMMS boundaries are defined by the program, the power users, and organization's stakeholders and includes categories that can capture the evaluator's perceived system's ability to interact with other systems using a balanced scorecard. The scores are based on the evaluator's operational experience with the CMMS' functions.

$$\text{MOE-b} = B.C._{1} \times W_{1} + B.C._{2} \times W_{2} \ldots + B.C._{n} \times W_{n} = \sum_{i=1}^{n} B.C._{i} W_{i}$$

Where $B.C_{i} = B.C._{1}, B.C._{2}, \ldots B.C._{n}$ are the average individual functional boundary conditions balanced scorecard scores and $W_{i} = W_{1}, W_{2}, \ldots W_{n}$ are the weights associated with each category. MOE-b provides a metric that captures the system's aggregate functional

boundary conditions score. A low MOE score indicates opportunities for improvement by addressing the interaction between the system's functions and external systems.

c. Procedure-User

The procedure-user cardinal point addresses the process and mechanisms that describe user behaviors due to the CMMS (G. O. Langford 2012, 90). The cardinal point involves the influence of CMMS procedures on user behavior (G. Langford, Determinants of Deterrence Effectiveness 2014, 23). Some questions that arise in determining the procedure-user cardinal point evaluation factors are (G. O. Langford 2012, 90-91):

- Do the CMMS procedures enable good sense decisions?
- Do the CMMS procedures enable the production of credible work?
- Do the CMMS procedures show resilience to change?
- Are the CMMS procedures novel?

Procedure-user MOEs are not developed in this research. These MOEs are better developed once a CMMS has been selected and implemented and is being operated by all the maintenance management users. The organization members determined to be users will shape this cardinal point.

3. Model and Representation Domain

The model and representation domain ascribes meaning to the CMMS by evaluating models and representations of the system, its functions, and the users expectations based on these models. The model and representation domain MOEs are not developed in this research. These MOEs are better developed once a CMMS has been selected and implemented within an organization. The other systems and available peripherals will shape this domain.

H. MOE TO NEEDS TRACEABILITY

The modified nine step MOE development methodology results in a set of eight MOEs that address the Cognition-Object, Cognition-Function, Procedure-Object, and Procedure-Function cardinal points of the integrative framework. Each developed MOE

measures a CMMS aspect that is traceable to the system requirements derived from the stakeholder needs. A traceability matrix tracing the developed MOEs to the original set of stakeholder needs is illustrated in Table 5. The system requirements are summarized in Table 6 and the eight developed MOEs are summarized in Table 7.

Table 5. Traceability matrix

		Stakeholder Requirements												
		1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0
Measures of Effectiveness	MOE-e	X			X	X	X	X	X	X	X	X	X	
	MOE-r	X				X	X	X	X					
	MOE-g	X					X	X	X	X	X	X	X	
	MOE-c					X	X	X	X	X	X	X	X	
	MOE-s	X	X	X			X		X	X	X	X	X	X
	MOE-x	X	X	X	X	X	X	X	X					
	MOE-u	X				X	X		X	X	X	X		X
	MOE-b	X	X	X	X	X	X	X	X	X		X		

The traceability matrix in Table 5 illustrates that each stakeholder requirement that may be used in determining the CMMS' fitness-for-purpose is addressed by at least one MOE from the developed set.

Table 6. CMMS requirements summary

1.0	The CMMS shall display a customizable dashboard that provides decision makers with all the required necessary information to conduct maintenance management and other related tasks.
2.0	The CMMS shall be scalable to different classes of hardware and software platforms.
3.0	The CMMS shall be operable with different classes of hardware and software platforms.
4.0	The CMMS shall be customizable.
5.0	The CMMS shall possess a web browser user interface that provides the user with the most up-to-date maintenance data.
6.0	The CMMS shall generate reports to facilitate analysis of equipment reliability, maintainability, sustainability, consumption, and performance as required to support maintenance management.
7.0	The CMMS shall generate a work-order list by user modified query.
8.0	The CMMS shall generate an accurate integrated work-order execution schedule.
9.0	The CMMS shall record and maintain equipment maintenance data.
10.0	The CMMS shall provide all users a common maintenance status.
11.0	The CMMS shall allow users to coordinate and share maintenance requirements.
12.0	The CMMS shall maintain work execution status.
13.0	The CMMS should not require periodic licensing.

Table 7. MOE summary

MOE	Description	Calculation
MOE-e: CMMS experience	Cognition-Object: Provides insight into the effectiveness of system usage as it relates to recording, updating, coordination, and communication of maintenance data.	$\frac{\text{\# Task Elements Completed Using CMMS}}{\text{\# Available Task Elements Expected to be Completed Using CMMS}}$
MOE-r: CMMS Response	Cognition-Object: Provides insight into the effectiveness of the management and reporting of maintenance data and the system's interface with objects.	$\frac{\text{\# Work Orders Requiring Administrative Rework}}{\text{\#Work Orders}}$
MOE-g: CMMS Functionality Prediction	Cognition-Function: Provides insight into the effectiveness of the predicted functional results arising from interactions between the systems and data reporting objects.	$F.C._1 \times W_1 + F.C._2 \times W_2 ... + F.C._n \times W_n = \sum_{i=1}^{n} F.C._i W_i$
MOE-c: CMMS Functionality Expectation	Cognition-Function: Identifies user satisfaction based on system expectations.	$F.C.E._1 \times W_1 + F.C.E._2 \times W_2 ... + F.C.E._n \times W_n = \sum_{i=1}^{n} F.C.E._i W_i$
MOE-s: CMMS Selection Validity	Procedure-Object: Identifies the high level stakeholder's satisfaction based on programmatic goals.	$S.F._1 \times W_1 + S.F._2 \times W_2 ... + S.F._n \times W_n = \sum_{i=1}^{n} S.F._i W_i$
MOE-x: CMMS Operational Context Validity	Procedure-Object: Identifies the CMMS' ability to interact with external objects.	$O.C._1 \times W_1 + O.C._2 \times W_2 ... + O.C._n \times W_n = \sum_{i=1}^{n} O.C._i W_i$
MOE-u: CMMS Functional Resource Utilization Validity	Procedure-Function: Provides insight into the efficiency of the CMMS' functions to support resource management.	$F.S._1 \times W_1 + F.S._2 \times W_2 ... + F.S._n \times W_n = \sum_{i=1}^{n} F.S._i W_i$
MOE-b: CMMS Functional Boundary Conditions	Procedure-Function: Provides a metric of the CMMS' function's ability to interact with external objects.	$B.C._1 \times W_1 + B.C._2 \times W_2 ... + B.C._n \times W_n = \sum_{i=1}^{n} B.C._i W_i$

VI. MEASURES OF EFFECTIVENESS SET DEVELOPMENT FINDINGS, LIMITATIONS, AND CONCLUSIONS

A. MAJOR FINDINGS

The nine-step methodology provides a repeatable process to successfully develop a set of measures of effectiveness (MOE) based on stakeholder needs, requirements, and system limitations to determine the fitness-for-purpose of a computerized maintenance management system (CMMS) and its employment.

The effective implementation of a Conditioned Based Maintenance Plus (CBM+) strategy relies on the effective use of a suitable CMMS program. The lack of well-defined and methodically derived MOEs is a consequence of the absence of a consistent methodology to measure CMMS implementation effectiveness as it pertains to CBM+. Well-defined MOEs help determine and monitor how well the selected CMMS program accomplishes its intended operational objectives. Currently there is no standard method to develop MOE sets based on objective values and subjective criteria. A well-developed CMMS MOE set may be used by a maintenance organization in evaluating the CMMS' fitness-for-purpose throughout its lifecycle.

A set of CMMS MOEs was developed in Chapter V using a modification of Langford's nine-step methodology (G. Langford, Determinants of Deterrence Effectiveness 2014, 7-11). The nine-step method is a systems engineering (SE) focused approach that uses an integrative framework of objective values and subjective criteria to guide the development of MOEs.

The method consists of a repeatable process and allows for iterations based on requirements derived from stakeholder needs. The nine-step method's repeatability allows the maintenance organization to periodically determine the effectiveness of their CMMS employment. Every periodic evaluation should indicate opportunities for the organization's personnel, and maintenance processes and mechanisms to improve.

B. SIGNIFICANCE OF MAJOR FINDINGS

A maintenance organization may use the developed set of eight CMMS MOEs to determine how well the CMMS is being employed within the organization and how well it supports a CBM+ approach. The MOE set provides basic indicators to determine the effectiveness of the CMMS function's and of the system as an object. The developed MOEs also address the initial set of stakeholder requirements and needs.

Maintenance organizations can use the development processes established by the nine-step methodology to develop valid, significant, and useful MOEs for system's fitness-for-purpose evaluation and determination. The nine-step method is practicable within a typical surface maintenance organization. Developing and iterating MOEs will only require staff with an understanding of the overarching programmatic goals and knowledge of the evaluated systems due to the method's simple and direct approach. The process could also be extended to MOE development in other areas.

The developed CMMS MOEs have the characteristics specified in the works reviewed in Chapter III.

The works of Roedler and Jones (2005, 36) and Stevens (1986, 55) describe some of the traditionally accepted MOE characteristics, such as:

- Provide insight into at least one requirement
- Provide insight into different aspects of the alternative
- Shall not be predefined
- Should be relevant
- The set should be complete
- Should be precisely defined
- Should be expressed in terms that are meaningful to testers and developers
- Meaning should not be open to interpretation with the passage of time
- Inputs should be measureable
- Measurements should not interfere with system operation
- All qualitative measurements should use the same standard.

The nine-step methodology also enables the development of an MOE set that addresses the five different organizational levels in Wireman's performance pyramid (2005, 220). The five levels are: corporate, financial, tactical, functional, and their link to efficiency and effectiveness.

C. LIMITATIONS

Due to the scope of this research, the nine-step method was modified to include only the first seven steps. The successful completion of 'Step 7: Formalize Integrative Framework' produces an initial set of MOEs based on requirements, needs, and the system's functional limitations. Steps eight and nine address the implementation of the developed MOEs and are more applicable for an organization that is performing the developed measurements to determine the effectiveness of the system.

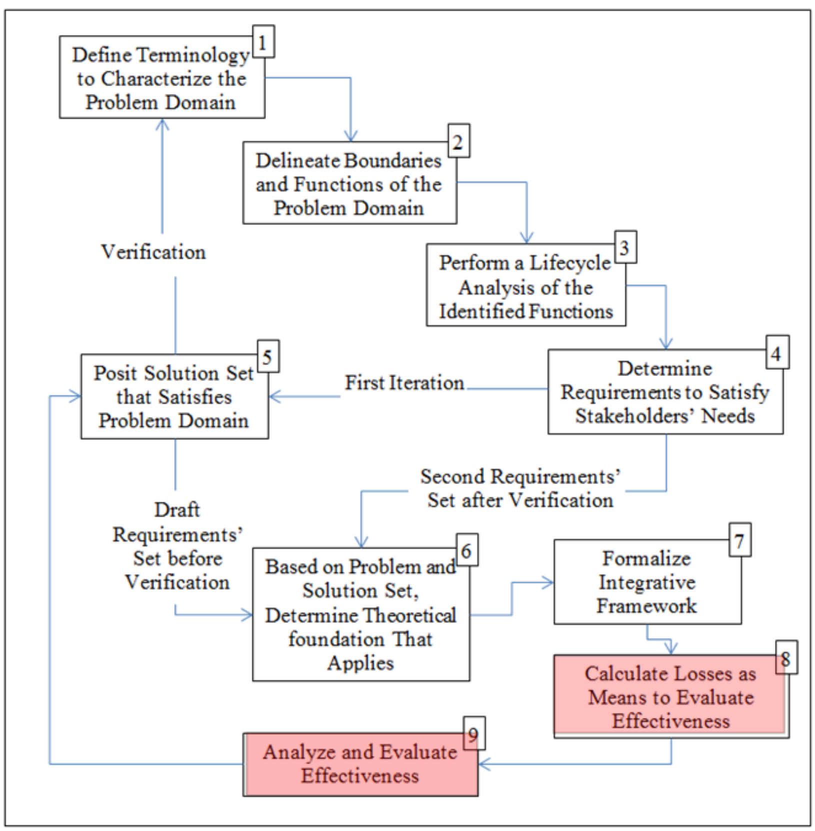

Figure 20. Nine step methodology to characterize MOEs (from G. Langford, Determinants of Deterrence Effectiveness 2014, 12)

The integrative framework was formalized using four of the possible nine cardinal points. The cardinal points in the process frame's 'models and representations' and the object frame's 'user behaviors' domain were addressed but MOEs were not developed. MOE development and analysis within these domains' cardinal points should be performed once a CMMS is established as a program-of-record. Once the CMMS becomes a program-of-record it will be operated under a set of standard policies and procedures that will govern all users. The surface maintenance organizations advancing the CBM+ implementation are currently in the CMMS selection and implementation stages. The CMMS programs currently being used are operated mostly by contractors; government maintenance organization personnel CMMS access is usually limited to data receivers. MOEs related to user behaviors towards the CMMS and its functions can be better developed once the maintenance organizations establishes a specific CMMS as the organization's premier management tool and the users become familiar with it.

		Processes		
		Cognition	Procedures	Models & Representations
Objects	User Behaviors	Conceptualization of stakeholder behaviors **(MOE-a)** when the product*service is used; and when it not used (or available) **(MOE-p)**	Influence of procedures on processes and mechanisms describing user behaviors due to product*service **(MOE-i)**; Influence describing user behaviors due to lack of product*service **(MOE-f)**	Comparison of expectations of models or representations of stakeholder behaviors to actions **(MOE-t)**; Evaluation of behaviors to predicted actions **(MOE-v)**
	Functions	Prognostication of consequences of interactions between objects through exchange of EMMI **(MOE-g)**; & Expectations of interactions **(MOE-c)**	Availability and Validity of processes and mechanisms that determine resource utilizations for functions **(MOE-u)**; Processes and mechanisms that define the boundary conditions for anticipated operations of all functions **(MOE-b)**	Models/representations showing all functional performances **(MOE-n)**; Models/representations showing all functional performance's quality **(MOE-q)**
	Physical Entities - Object	Experience with posited objects **(MOE-e)** & anticipated responses of posited objects **(MOE-r)**	Availability and Validity of processes and mechanisms resulting in the selection and development of all physical elements **(MOE-s)**; Processes and mechanisms resulting in the development of all physical elements and operational contexts **(MOE-x)**	Models or representations of all physical elements, (structures, properties, traits, and attributes **(MOE-o)**; Models or representations of all social, political, economic elements **(MOE-j)**

Figure 21. MOE Framework Cardinal Points (from G. Langford Building the Determinants of Technology Effectiveness 2014, 12)

D. FURTHER RESEARCH

The scope and limitations of this project leave opportunities for further research concerning MOE development and CMMS MOE analysis.

Further research should develop CMMS MOEs for a maintenance organization that uses a fully employed program-of-record CMMS. Once the CMMS is fully employed as a program-of-record, the stakeholder input will be based on the consequences of the established policies and procedures governing the system. The research can extend CMMS MOE development to the nine integrative framework cardinal points using the nine-step method based on the stakeholder's revised needs and in-service requirements iterations.

Although the nine-step methodology is practicable within most maintenance organizations further research should explore other repeatable MOE development alternatives.

E. CONCLUSION

The nine-step method provides a consistent approach that may be used as a tool to develop significant MOEs that evaluate the successful operational use of a CMMS program in the implementation of a CBM+ strategy using subjective and objective criteria.

Maintenance organizations should adopt a consistent methodical approach, such as the nine-step method, to evaluate the fitness-for-purpose of their maintenance management systems. The consequence of not using a methodical approach to develop MOEs is that the maintenance organization might waste time, money, and other limited resources by measuring inappropriate program characteristics that are not true indicators of the system's success. Additionally, not getting a true measure of a system's effectiveness will prolong the inefficient use of a possibly capable system.

Meaningful, observable, quantifiable, and precise MOEs provide the most significant criteria to assess the quality of a CMMS, the services it provides, and its usage.

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APPENDIX A. GLOSSARY

adaptability

“Attributes of software that bear on the opportunity for its adaptation to different specified environments without applying other actions or means than those provided for this purpose for the software considered” (INCOSE 1998, 12).

balanced scorecard

Strategic planning and management system that aligns activities with the overarching goals of an organization and measures performance against specific goals. (Balanced Scorecard Institute 2014)

boundary conditions

1. “Mediation of capabilities that enact across boundaries” (G.O. Langford 2012, 43).
2. Description of “the conditions which determine the interaction between two objects” (G. O. Langford 2012, 43).

effectiveness

1. “The extent to which the goals of the system are attained” (INCOSE 1998, 71).
2. “The degree to which a system can be elected to achieve a set of specific mission requirements” (INCOSE 1998, 71).

flexibility

Attribute of software that refers to its ability to adapt to external changes (Wikipedia 2013).

function

1. “An action/task that the system must perform to satisfyy customer and developer needs” (INCOSE 1998, 98).
2. “The action or actions, which an item is desidned to perform” (INCOSE 1998, 98).

legacy system

“Systems that are candidates for phase-out, upgrade, or replacement” (INCOSE 1998, 128).

maintenance

1. “Those actions required to restore or maintain an item to a serviceable condition” (INCOSE 1998, 136).
2. “The combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function” (INCOSE 1998, 137).

measure of effectiveness

“A metric used to quantify the performance of system products and processes in terms that describe the utility or value when executing customer missions” (INCOSE 1998, 144).

mechanism
“The technical aspects of doing something” (WordWeb 2014).

object
“Anything physical, comprised of matter or energy in ways that manifest as physical properties” (G. O. Langford 2012, 44).

operational context
The external environment that influences an object’s operation (Wikipedia 2013)

organizational level maintenance
“The maintenance and repair performed by the activity level (organization) which uses the system's equipment, within the activity's capability” (Cochrane 1995).

performance drivers
“Critical success factors that determine whether business and marketing objectives are achieved” (SensaCom n.d.).

power user
A user who has the ability to use advanced features of programs which are beyond the abilities of average users, but is not necessarily capable of computer programming and system administration (Wikipedia 2013).

program of record
“Program as recorded in the current Future Years Defense Program (FYDP) or as updated from the last FYDP by approved program” (Defense Acquisition University 2010).

scalability
“The ability to use the same application software on many different classes of hardware/software platforms” (INCOSE 1998, 210).

suitableness
“The quality of having the properties that are right for a specific purpose” (WordWeb 2014).

Technical Authority
“The authority, responsibility, and accountability to establish, monitor, and approve technical standards, tools and processes in conformance to higher authority policy, requirements, architectures, and standards” (Naval Sea Systems Command 2008, 8-5).

validation

Steps taken to ensure that a system meets the requirements (INCOSE 1998, 280)

value stream mapping

A lean-manufacturing technique that analyzes and designs flow at the system level with the objective of identifying waste in the current state of a service process. (Wikipedia 2013)

waste

1. Any non-required step or action in a process. (GoLeanSixSigma.com n.d.)

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APPENDIX B. CMMS IMPLEMENTATION SURVEY RESULTS – 2000

These are the results from a CMMS implementation survey conducted in 2000 by the Plant Maintenance Resource Center. (The Plant Maintenance Resource Center 2009)

Overview

This survey of CMMS Implementation was conducted on the Plant Maintenance Resource Center website between June and August 2000.

Summary of Key Findings

Voluntary (and confidential) responses were sought to the survey, and 87 valid responses were received from a wide range of individuals working across a variety of industries.

The key findings are:

Most respondents reported some or significant benefits as a result of their CMMS implementation, however a significant proportion (between 20 and 40%) of respondents either were unable to identify any benefits, or reported no benefits.

- Overall, a significant 20% of respondents rated their CMMS implementation as poor.
- Overall, it would appear that conducting BPR seems to increase the chances of successful implementation- although, on its own, still not increasing the chance of success above 50%.
- Statistical analysis of responses showed no clear correlation between the conduct of other usual change management activities associated with CMMS implementation, and the perception of implementation success
- However, the factors stated by respondents as being important were obtaining management commitment, selecting the correct CMMS, and effective training.
- In contrast, those currently considering replacing or upgrading their CMMS place a far higher emphasis on selecting the correct CMMS, and do not consider training to be an important implementation issue.
- The most common CMMS in use by respondents were Maximo, MP2, SAP and MIMS.

- Most CMMS were seen as being relatively easy to use, with the exception of SAP. SAP was also considered by some, to be functionally poor.
- In terms of the perception of success, Maximo implementations were generally seen as successful, while SAP users were divided - it appears that you either love SAP or hate it.

Respondent Data

Of the 87 valid responses, just over half were based in the USA, with Australia, Canada, and the United Kingdom also well represented.

Country	Responses	% of Total
United States	48	55.2%
Australia	11	12.6%
United Kingdom	4	4.6%
Canada	3	3.4%
New Zealand	2	2.3%
South Africa	2	2.3%
Thailand	2	2.3%
Belgium	1	1.1%
Chile	1	1.1%
Indonesia	1	1.1%
Netherlands	1	1.1%
Norway	1	1.1%
Spain	1	1.1%
Other/Not Specified	9	10.3%

Respondents came from a wide range of industries.

Industry	Responses	% of Total
Manufacturing: Other	15	17.2%
Manufacturing-Metal products	10	11.5%
Manufacturing-Food, beverages, tobacco	7	8.0%
Utilities-Electricity Generation	7	8.0%
Manufacturing-Petroleum refining, chemicals and associated products	5	5.7%
Manufacturing-Wood and paper products	5	5.7%
Oil and Gas-Oil and gas extraction	5	5.7%

Industry	Responses	% of Total
Manufacturing-Machinery and equipment	4	4.6%
Services-Healthcare	3	3.4%
Services-Property services/Building Maintenance	2	2.3%
Manufacturing-Non-metallic mineral processing	1	1.1%
Mining-Metal ore	1	1.1%
Mining-Other	1	1.1%
Services-Education/Academia	1	1.1%
Services: Research & Development	1	1.1%
Services-Telecommunications	1	1.1%
Utilities-Electricity Transmission and Distribution	1	1.1%
Utilities-Water, sewerage, drainage	1	1.1%
Other/Not Specified	15	17.2%

Maintenance line management positions and Maintenance Engineering positions were well represented in the survey.

Position	Responses	% of Total
Maintenance Manager/Superintendent	24	27.6%
Maintenance Foreman/Supervisor	12	13.8%
Maintenance Planner	9	10.3%
Plant/Maintenance Engineer	9	10.3%
Reliability Engineer	3	3.4%
CEO/Managing Director	3	3.4%
Maintenance Contract Manager	2	2.3%
Product Support Manager	2	2.3%
Software Support Manager	2	2.3%
Software Support Professional	2	2.3%
Consulting Engineer	2	2.3%
Maintenance Crafts/Tradesperson	1	1.1%
Maintenance Technician	1	1.1%
Process/Industrial Engineer	1	1.1%
Software Support Technician	1	1.1%
Management Consultant	1	1.1%
Other/Not Specified	12	13.8%

Respondents generally came from larger and medium sized organizations

No of Trades/Craftspeople	Responses	% of Total
Large(more than 100 crafts/tradespeople)	41	47.1%
Medium(10 to 100 crafts/tradespeople)	30	34.5%
Small(less than 10 crafts/tradespeople)	10	11.5%

Detailed Results

Full statistical survey results can be viewed here. This article focuses on some of the more interesting results, and also reviews the correlation between some of the survey results in order to determine what factors (if any) are more likely to lead to successful CMMS Implementation.

CMMS usage

Almost 90% of respondents are currently using a CMMS.

Does your workplace currently use a CMMS?		
	Responses	% of Total
Yes	78	89.7%
No	9	10.3%

The most common CMMS in use include Maximo, SAP, MP2, and MIMS.

Which CMMS does your workplace currently use?		
CMMS	Responses	% of Total
Maximo	16	18.4%
SAP	12	13.8%
MP2	11	12.6%
MIMS	5	5.7%
Mainpac	3	3.4%
Mainsaver	2	2.3%
MS2000	2	2.3%
PMC	2	2.3%
Tabware	2	2.3%

Which CMMS does your workplace currently use?		
CMMS	Responses	% of Total
AMMS	1	1.1%
Benchmate	1	1.1%
Developed in-house	1	1.1%
Elke	1	1.1%
Frontline	1	1.1%
GPMate	1	1.1%
IMMPOWER	1	1.1%
Impactxp	1	1.1%
Insight Plant Maintenance System	1	1.1%
Mainstar	1	1.1%
Maintain it	1	1.1%
Maintenance Manager	1	1.1%
Maintenance Tracker	1	1.1%
MAPCON	1	1.1%
Marcam PRISM	1	1.1%
MCP	1	1.1%
Mex	1	1.1%
OCS Materials Management	1	1.1%
Passport	1	1.1%
pcmaint32	1	1.1%
PERMAC	1	1.1%
PM Plus	1	1.1%
Somax	1	1.1%
Ultimo	1	1.1%
Other/Not Specified	8	9.2%

Most systems have been in place only for a few years.

How long ago did you "go live"?		
Years	**Responses**	**% of Total**
In progress	9	10.3%
<1 year	12	13.8%
1-2 years	20	23.0%
2-3 years	9	10.3%
3-4 years	5	5.7%
>4-5 years	10	11.5%
>5 years	14	16.1%

Reasons for selecting and implementing a CMMS

Many CMMS Implementations were conducted with the expectation that they would lead to improved maintenance performance. However, there were also many other reasons for implementing a CMMS.

What was the main reason that your workplace changed CMMS, or implemented a new CMMS?		
Reason	**Responses**	**% of Total**
To improve maintenance performance	25	28.7%
Improved functionality and features	16	18.4%
To integrate the Maintenance system with other systems	9	10.3%
Don't know	8	9.2%
Year 2000 compliance problems	7	8.0%
Vendor no longer supported our old CMMS	2	2.3%
To comply with company standards	2	2.3%
To use newer technology	1	1.1%
Other	7	8.0%

A large proportion of respondents were not aware of the reasons for selection of the current CMMS.

What was the most/second most important reason that your workplace chose your current CMMS?				
	Most Important		Second Most Important	
Reason	Responses	% of Total	Responses	% of Total
Availability of local support	2	2.3%	1	1.1%
Compatibility with previous CMMS software	2	2.3%	1	1.1%
Don't know	20	23.0%	23	26.4%
Ease of implementation	1	1.1%	5	5.7%
Ease of Use	11	12.6%	8	9.2%
General functionality and features	16	18.4%	15	17.2%
Integration with other commercial software	9	10.3%	5	5.7%
Other	9	10.3%	4	4.6%
Price	7	8.0%	6	6.9%
Speed of system response	1	1.1%	1	1.1%

CMMS Comparison

Overall, CMMS are seen as being moderately easy to use, with Maximo rating highly, and SAP seen as being harder to use.

How would you rate your current CMMS in terms of its ease of use?					
	No of Responses				
CMMS	Excellent	Very Good	Good	Satisfactory	Poor
Maximo	5	5	3	3	
MP2	1	3	4	2	1
SAP		4	2	1	5
MIMS		1	2	1	1
Other	4	8	14	6	3
Total	**10**	**21**	**25**	**13**	**10**

Most CMMS are seen as being well endowed with functionality and features, although again, SAP rates poorly according to some.

How would you rate your current CMMS in terms of its general features and functionality?					
	No of Responses				
CMMS	Excellent	Very Good	Good	Satisfactory	Poor
Maximo	5	5		3	1
MP2	1	4		2	1
SAP	2	3			6
MIMS		4		1	
Other	5	9		3	6
Total	**13**	**25**		**9**	**14**

Maximo implementations are generally seen as successful, while SAP users either love it, or hate it. Overall, a significant 20% of respondents rated their implementation as poor.

Overall, how would you rate the success of your CMMS implementation?					
	No of Responses				
CMMS	Excellent	Very Good	Good	Satisfactory	Poor
Maximo	1	8	3	2	2
MP2	1	2	4	2	2
SAP	3	3		1	5
MIMS			3		2
Other	2	7	10	9	6
Total	**7**	**20**	**20**	**14**	**17**

Factors Influencing Implementation Success

If you look at the results for the question of Business Process Reengineering (BPR) impact on implementation success you see that of respondents that had conducted BPR 16 rated their success as Good to Excellent and 4 rated their success as Satisfactory to Poor. (4 to 1 ratio). If you compare that to respondents that did not conduct BPR where 25 rated Good to Excellent and 20 rated Satisfactory to Poor (5-4 ratio). This is a significant indicator that

there was a larger percentage of dissatisfaction if BPR was not conducted, and so it could be said that BPR is a significant factor contributing to implementation success. On the other hand, if you look at the proportion of those who rated their implementation as Excellent or Very Good, compared with those who considered it Satisfactory or Poor, in both cases, the majority of respondents had not conducted BPR (13 of 23, ignoring the Don't Knows, and 20 of 24, respectively). This indicates that conducting BPR was not a significant factor in assisting with implementation success. Overall, however, it would appear that conducting BPR does seem to increase the chances of success - although, on its own, still not increasing the chance of success above 50%.

Impact of Business Process Reengineering on Implementation Success					
	How do you rate success of Implementation? No of Responses				
BPR Conducted?	**Excellent**	**Very Good**	**Good**	**Satisfactory**	**Poor**
Yes	4	6	6	2	2
No	2	11	12	11	9
Don't Know	1	3	2	1	5
Total	**7**	**20**	**20**	**14**	**16**

Using consultants to assist with implementation also appears to have minimal influence on the perception of implementation success.

Impact of Consultants on Implementation Success					
	How do you rate success of Implementation? No of Responses				
Used Consultants?	**Excellent**	**Very Good**	**Good**	**Satisfactory**	**Poor**
Yes	3	9	5	5	7
No	4	10	14	8	6
Don't Know		1	1	1	4
Total	**7**	**20**	**20**	**14**	**17**

Issuing regular newsletters during implementation also appears to have minimal influence on the perception of implementation success.

Impact of Newsletters on Implementation Success					
	How do you rate success of Implementation? No of Responses				
Issued Newsletters?	**Excellent**	**Very Good**	**Good**	**Satisfactory**	**Poor**
Yes	4	2	5	3	8
No	2	14	15	11	4
Don't Know	1	3			4
Total	**7**	**19**	**20**	**14**	**16**

Performing regular face-to-face briefings during implementation appears to have a minor influence on the perception of implementation success.

Impact of Face to Face Briefings on Implementation Success					
	How do you rate success of Implementation? No of Responses				
Regular Briefings?	**Excellent**	**Very Good**	**Good**	**Satisfactory**	**Poor**
Yes	5	13	12	9	6
No	1	5	8	4	7
Don't Know	1	2		1	4
Total	**7**	**20**	**20**	**14**	**17**

Establishing a help line during implementation appears to have a minor influence on the perception of implementation success.

Impact of a "Help Line" on Implementation Success					
	How do you rate success of Implementation? No of Responses				
Help Line?	**Excellent**	**Very Good**	**Good**	**Satisfactory**	**Poor**
Yes	4	10	12	6	9
No	2	6	10	8	4
Don't Know	1	2			3
Total	**7**	**20**	**20**	**14**	**16**

Conducting regular stakeholder analysis during implementation, although not often done, appears to have a positive influence on the perception of implementation success.

Impact of Stakeholder Analysis on Implementation Success					
	How do you rate success of Implementation? No of Responses				
Stakeholder Analysis?	Excellent	Very Good	Good	Satisfactory	Poor
Yes	3	6	4	1	2
No	3	12	15	10	8
Don't Know	1	2	1	2	6
Total	**7**	**20**	**20**	**13**	**16**

Conducting Training Needs analysis as part of implementation appears to have a minor influence on the perception of implementation success.

Impact of Training Needs Analysis on Implementation Success					
	How do you rate success of Implementation? No of Responses				
Training Needs Analysis?	Excellent	Very Good	Good	Satisfactory	Poor
Yes	5	9	11	6	4
No	1	9	9	7	7
Don't Know	1	1		1	5
Total	**7**	**19**	**20**	**14**	**16**

Conducting Workforce Culture Surveys as part of implementation appears to have no influence on the perception of implementation success.

Impact of Culture Surveys on Implementation Success					
	How do you rate success of Implementation? No of Responses				
Culture Surveys?	Excellent	Very Good	Good	Satisfactory	Poor
Yes	5	4	5	3	2
No	1	14	14	8	11
Don't Know	1	1	1	3	3
Total	**7**	**19**	**20**	**14**	**16**

According to the respondents, the most important factors in their success were obtaining Senior Management commitment, and selecting the correct CMMS.

What do you consider are the two most important aspects of your implementation that led to your success?			
	Responses		
Factor	Most Important	Second Most Important	Total
Senior Management commitment	11	13	24
Choosing the right CMMS	13	6	19
Effective training	5	8	13
Focus on business benefits	8	5	13
Adequate budget	3	7	10
Effective Change Management	6	4	10
Effective Project Management	5	5	10
CMMS Vendor Support	5	2	7
Effective BPR	3	4	7
Consultant support	1	4	5
Other	13	7	20

Furthermore, the most important area in which respondents wished they had done better was in the area of training.

In hindsight, what is the most important aspect of your implementation that you should have spent more time and effort on, in order to increase implementation success?		
Factor	Responses	Percent
Effective training	21	24.1%
Choosing the right CMMS	17	19.5%
Senior Management commitment	8	9.2%
Effective BPR	8	9.2%
Effective Change Management	6	6.9%
Effective Project Management	5	5.7%
Adequate budget	3	3.4%
Focus on business benefits	3	3.4%
CMMS Vendor Support	1	1.1%
Other	2	2.3%

In comparison, those currently considering implementing a new CMMS place far greater importance on CMMS selection. Effective Training is not considered to be at all important.

What do you consider will be the most important aspect of your implementation that will lead to success?			
	Responses		
Factor	Most Important	Second Most Important	Total
Choosing the right CMMS	9	3	12
Senior Management commitment	2	3	5
Effective Change Management	2	3	5
Effective Project Management	2	1	3

Benefits obtained from CMMS Implementation

Overall, most respondents reported that their CMMS implementation has led to some or significant benefits. However a large proportion (between 20% and 40%) of respondents either reported achieving no business benefits from their CMMS implementations, or were unable to quantify benefits.

	Size of Benefits Obtained % of Responses			
Area of Benefit	Significant	Some	None	Don't Know
Reductions in Labor Costs	9.2%	37.9%	31.0%	11.5%
Reductions in Materials Costs	11.5%	43.7%	20.7%	13.8%
Reductions in Other Costs	10.3%	43.7%	20.7%	13.8%
Improved Equipment Availability	21.8%	33.3%	25.3%	9.2%
Improved Equipment Reliability	21.8%	35.6%	24.1%	8.0%
Improved Cost Control	44.8%	26.4%	16.1%	2.3%
Improved Maintenance History	46.0%	18.4%	23.0%	2.3%
Improved Maintenance Planning	32.2%	36.8%	18.4%	2.3%
Improved Maintenance Scheduling	31.0%	36.8%	18.4%	2.3%
Improved Maintenance Schedules	37.9%	32.2%	16.1%	2.3%
Improved Spare Parts Control	24.1%	37.9%	23.0%	4.6%

Amazingly, only 20% of organizations responding have attempted to formally quantify the benefits obtained from their CMMS implementation.

Has your workplace formally measured the benefits of your CMMS implementation?		
	Responses	**% of Total**
Yes	17	19.5%
No	51	58.6%
Don't Know	9	10.3%

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